A Low-Power Ka -Band Voltage-Controlled Oscillator Implemented in 200-GHz SiGe HBT Technology

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Abstract—An integrated low-power low phase-noise Ka -band differential voltage-controlled oscillator (VCO) is developed in a 0.12- μm 200-GHz silicon-germanium heterojunction bipolar transistor technology. The use of line inductors instead of transmission lines is demonstrated to be feasible in LC-tuned resonators for Ka -band applications. This VCO can operate from a supply voltage of 1.6–2.5 V. A single-sideband phase noise of -99 dBc/Hz at 1-MHz offset from the carrier frequency of 33 GHz is achieved, together with a VCO figure-of-merit of -183.7 dBc/Hz. The frequency tuning constant of the VCO in the linear regime is -0.547 GHz/V.

Index Terms—Heterojunction bipolar transistor (HBT), Ka -band, line inductor, low power, microstrip line, $1/f$ noise, phase noise, silicon-germanium (SiGe), voltage-controlled oscillator (VCO).

I. INTRODUCTION

INTEGRATED voltage-controlled oscillators (VCOs) for Ka -band applications have been historically developed using either GaAs or other III–V technologies, given that sufficient cutoff frequency (f_T) and maximum frequency of oscillation (f_{max}) around or beyond Ka -band are very difficult to achieve in silicon (Si) technology [1]–[6]. In addition, the lossy Si substrate also places serious constraints on the implementation of on-chip passive components such as inductors and transmission lines that are required for numerous Ka -band circuit functions. With the rapid progress made in

silicon-germanium (SiGe) heterojunction bipolar transistor (HBT) technology, however, fully Si-manufacturing-compatible SiGe HBTs with a peak f_T of over 200 GHz and a peak f_{max} of over 250 GHz are now commercially available [7], and the record peak f_T of SiGe HBTs has at present reached 350 GHz [8]. These SiGe HBTs also offer extremely low $1/f$ and broad-band noise, making them ideally suited for low phase-noise oscillators. Thus, the intrinsic performance capability of Si-based technologies is no longer a bottleneck for Ka -band circuit applications, and there has been recent interest in developing SiGe VCOs [9]–[12].

The high f_T and f_{max} of SiGe HBTs not only make VCOs at Ka -band practical, but also facilitate a true power-aware design paradigm. SiGe HBT BiCMOS technology nicely enables the trend toward increased levels of integration with more transistors and functionality effectively squeezed onto a single chip. Since SiGe technology is much more easily scaled than conventional III–V technologies, the high f_T and f_{max} achieved with a 200-GHz SiGe technology at very small device geometries allows SiGe HBTs to deliver adequate gain and noise required for the Ka -band applications, even at extremely low current density. This inherent low-power design advantage of SiGe technology can help relieve the serious power dissipation constraints faced at the package level and extend the battery life of portable components.

The realization of high-quality on-chip passive elements, especially inductors and transmission lines, however, poses a major technical difficulty for using SiGe technology for applications above 10 GHz. On-chip inductors in Si were once thought to be impractical for the implementation of RF integrated circuits (RFICs) in the early 1990s because of the lossy substrate and the thin metal interconnections, which significantly degrade the quality factor (Q) of the inductors. Research into Q enhancement of spiral inductors on Si, however, has led to feasibility demonstrations of adequate on-chip inductors to as high as 10 GHz. Passive elements for monolithic microwave integrated circuit (MMIC) applications above 10 GHz are mostly made using microstrip or coplanar transmission-line techniques.

This paper presents a fully integrated low-power Ka -band VCO, which uses line inductors in its resonators and is implemented in a state-of-the-art 0.12- μm 200-GHz SiGe HBT technology [27]. A VCO figure-of-merit (FOM) of -183.7 dBc/Hz has been achieved, which is comparable to or better than the best

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Fig. 1. Schematic cross section of raised extrinsic base SiGe HBT.

published results for both SiGe VCOs [9]–[17] and *Ka*-band VCOs implemented in III–V technology [1]–[6].

II. RAISED EXTRINSIC BASE SiGe HBTs

A. SiGe HBT Technology

The SiGe HBT technology used in the current investigation employs a novel reduced thermal cycle “raised extrinsic base” structure, and utilizes conventional deep and shallow trench isolation, an *in situ* doped polysilicon emitter, and an unconditionally stable 25% peak Ge C-doped graded ultra-high vacuum (UHV)/chemical vapor deposition (CVD) epitaxial SiGe base. The device structure has been scaled laterally to 0.12- μm emitter stripe width in order to minimize base resistance and, thus, improve the frequency response and noise characteristics. Such a raised extrinsic base structure facilitates the elimination of any out diffusion of the extrinsic base, thereby significantly lowering the collector–base junction capacitance. The schematic SiGe HBT cross section is shown in Fig. 1.

B. AC Characteristics

The SiGe HBTs used in this VCO delivers an f_T higher than 40 GHz at extremely low current density and a peak f_T , which exceeds 200 GHz. Fig. 2 shows the typical f_T and $f_{\max}$ of the raised extrinsic base SiGe HBT with respect to the collector current density (J_C). Observe that the ac performance of the SiGe HBTs is more than adequate for *Ka*-band applications at a J_C value, which is an order of magnitude lower than the value at which the peak f_T and $f_{\max}$ are achieved. This is a consequence of the reduced transistor parasitics of the raised extrinsic base device structure.

C. Low-Frequency Noise Characteristics

Fig. 3 shows the typical low-frequency noise spectra of the base current, which is the dominant low-frequency noise source in these SiGe HBTs. The noise measurement method can be found in [30]. As can be seen from this figure, this technology offers extremely low $1/f$ noise with a very small geometry, emitter area of $0.12 \times 5.0 \mu\text{m}^2$, as compared with III–V HBTs and MOSFETs [31]–[34]. The impact of $1/f$ noise on phase noise in VCOs even at high-frequency offset (e.g., 1 MHz) is a concern for most MOSFETs and III–V HBT-based VCOs operating at *Ka*-band. Due to the superior $1/f$ noise and low noise

Fig. 2. Typical f_T and $f_{\max}$ of the SiGe HBT with respect to the collector current density for $V_{CB} = 1$ V at room temperature. The emitter size of the SiGe HBT is $0.12 \times 2.5 \mu\text{m}^2$.

Fig. 3. Base current low-frequency noise spectra from an SiGe HBT with emitter area of $0.12 \times 5 \mu\text{m}^2$ at $I_B = 0.5, 1$, and $2 \mu\text{A}$.

corner frequency of this SiGe HBT technology, the up-converted $1/f$ noise to the phase noise at 1-MHz frequency offset from the carrier frequency is not significant.

III. LINE INDUCTOR DEVELOPMENT

Coplanar and microstrip lines are typically used to implement the inductive elements at *Ka*-band [1]–[6]. For this *Ka*-band VCO, however, line inductors are instead used to implement the resonators. The length of the line inductor is less than 2% of the transmission signal wavelength at *Ka*-band. Therefore, transmission-line effects are not significant for the line inductors in this VCO. The line inductors are made with the topmost metal layer of the four interconnection metal layers in order to increase the distance away from the lossy substrate. This arrangement helps mitigate the energy coupled into the substrate and also reduce the parasitic capacitance between the inductor line and substrate. The top metal is a 4- μm -thick Al, and is used to facilitate the development of low-loss interconnections, inductors, and transmission lines. In addition, the line inductors were im-

Fig. 4. Simulated inductance and Q of the spiral inductor and line inductor. The dashed lines represent the characteristics of spiral inductor and the solid lines represent that of line inductor.

plemented on top of the deep-trenched array in the substrate to minimize the impact of the lossy Si substrate. The self-inductance of the line inductor can be calculated by [18], [19]

$$L = 0.002\ell \cdot \left[\ln \left(\frac{2\ell}{\text{GMD}} \right) - 1.25 + \frac{\text{AMD}}{\ell} + \left(\frac{\mu}{4} \right) \cdot T \right] \quad (1)$$

where the geometric mean distance (GMD) and arithmetic mean distance (AMD) of the line inductor cross section are represented, L is the inductance in microhenrys, ℓ is the conductor length in centimeters, μ is the conductor permeability, and T is the frequency correction factor. The GMD of a conductor cross section is the distance between two imaginary filaments normal to the cross section, whose mutual inductance is equal to the self-inductance of the conductor. The AMD is the average of all possible distances within the cross section.

From the simulations using a commercial two-and-one-half-dimensional (2.5-D) electromagnetic (EM) solver [25], the line inductors work reasonably well at Ka -band. The simulated inductance and Q are shown in Fig. 4. The length and width of the line inductors used in the VCO circuit are 106 and 5 μm , respectively. The simulated inductance of the line inductor is 78 pH at 33 GHz. The three-quarter-turn spiral inductor of roughly the same inductance was also simulated with the same setup and the result is shown in Fig. 4. The dashed lines represent the effective inductance and Q of the spiral inductor, while the solid lines represent those of the line inductor. The Q of the line inductor is more than 20 at the frequency band of interest, whereas the Q of the spiral inductor is less than ten.

Compared with the spiral inductor, the current crowding effect is alleviated for the line inductor, thereby improving its performance. For a line inductor, the density of current flow is symmetrically distributed across the width of the metal trace, while that of the square or octagonal spiral inductor is not symmetrically distributed, especially at the regions where the trace turns the directions. The simulated current densities of the spiral and line inductors are shown in Fig. 5. The current density near the

Fig. 5. Density of current flow in spiral and line inductors. The simulation is performed using momentum in ADS.

Fig. 6. Simulated effective inductance and Q of the line inductor and microstrip line. The solid lines represent the inductance and Q of the line inductor and the dash lines represent those of the microstrip line.

inner corners is much larger than that near the outer corners as the current flow changes directions in the spiral inductor. The current crowding effect is more severe for the square than the octagonal spiral inductors. Consequently, the effective resistance of the spiral inductors is larger than that of the line inductors although the metal trace widths of these two kinds of inductors are the same.

The other alternative element for the line inductor is the microstrip line. Unlike for numerous III-V semiconductor technologies, there is no back-plane metallization in the SiGe HBT technology. The bottom metal layer is used as the ground plane and the microstrip line is implemented in the topmost metal layer. The distance between the ground plane and microstrip line is only 10.4 μm . To maintain a compact design, the width of the microstrip line is kept the same as the line inductor, i.e., 5 μm . The length of the microstrip line needs to be 154 μm , which is 45% longer than the line inductor, to have the VCO oscillating at 33 GHz. The simulated effective inductance and Q of the microstrip line and line inductor are shown in Fig. 6. The Q of the microstrip line is lower than that of the line inductor because of the long metal line and the parasitic capacitance between the line

Fig. 8. Signal power versus bias current of the Ka -band VCO. The circles represents the measured signal power and the solid line is the plot of their relationship in the second-order polynomial function.

Fig. 10. Oscillation spectrum of the Ka -band SiGe VCO operated on 2.4-V supply voltage. The signal power is -12 dBm because the connection loss in the measurement system is 6 dB.

Fig. 9. Die photograph of the integrated differential SiGe HBT VCO. The chip size is $730 \times 650 \mu\text{m}^2$.

second-order polynomial function. The simplified phase-noise model can be represented as a function of I_C

$$\Phi_n(I_C) \cong 10 \log \left\{ \frac{2KT \cdot F(I_C)}{p_s(I_C)} \cdot \left[1 + \left(\frac{f_o}{2Q_L f_m} \right)^2 \right] \right\}. \quad (9)$$

The optimal bias collector current $I_{C,\text{opt}}$ for low phase noise can be obtained by solving $\partial\Phi/\partial I_C = 0$. $I_{C,\text{opt}}$ is usually larger than I_C at which the excess noise is minimum.

V. MEASUREMENT RESULTS

A. Phase Noise FOM

The die size of the integrated differential SiGe HBT VCO is $730 \times 650 \mu\text{m}^2$, as shown in Fig. 9. The spectrum analyzer HP8565E with the phase-noise measurement module

Fig. 11. Measured SSB phase noise of the SiGe VCO on 2.4-V supply voltage at 32.74 GHz.

HP85671A was used to measure the characteristics of the VCO. The total loss of the connection from the measurement system to the device-under-test (DUT) is 6.1 dB and was used to calibrate the measured signal power. The VCO operates on a supply voltage of 1.6 to 2.5 V, and consumes minimum power of only 2.64 mW. The screen shot of the oscillation spectrum is shown in Fig. 10. The free-running frequency of the VCO is approximately 33 GHz, and the signal power is around -12 dBm without any matching or tuning. The measured single-sideband (SSB) phase noise is -99 dBc/Hz at 1-MHz frequency offset. The screen shot of the measured phase noise is shown in Fig. 11.

In order to compare the performance of this study with those of other published VCOs, the VCO FOM is used to normalize

TABLE I
FOM COMPARISON OF LOW PHASE-NOISE SiGe VCOs

Reference	[9]	[10]	[11]	[20]	[21]	[22]	[23]	This Work
Technology	SiGe	SiGe	SiGe	SiGe	SiGe	SiGe	SiGe	SiGe
Oscillation Freq.	41 GHz	40 GHz	28 GHz	37 GHz	11 G	2.4 G	47 GHz	33 GHz
Figure-of-Merit	-155.1	-168.0	-152.3	-171	-184.2	-179.4	-177.5	-183.7

TABLE II
FOM COMPARISON OF PUBLISHED *Ka*-BAND III–V VCOs

Reference	[1]	[2]	[3]	[5]	[24]	This Work
Technology I	nGaP/GaAs	GaAs HBT	InGaAs/InP	AlGaAs/InGaAs	InP	SiGe
Oscillation Freq.	41 GHz	41 GHz	34 GHz	42 GHz	37 GHz	33 GHz
Figure-of-Merit	-190.8	-182.6	-186.0	-158.1	-157.3	-183.7

Fig. 12. Oscillation frequency of the SiGe VCO with respect to frequency-control voltage from 0 to 2.5 V at a fixed 2.5-V supply voltage.

the phase noise with respect to oscillation frequency, power consumption, and frequency offset according to

$$\text{FOM} = \Phi_n(f_m) - 20 \log \frac{f_o}{f_m} + 10 \log \frac{P_{\text{diss}}}{1 \text{ mW}} \quad (10)$$

where P_{diss} is the power dissipated by the VCO. This *Ka*-band SiGe HBT VCO achieves a FOM of -183.7 dBc/Hz, which is one of the best VCO results demonstrated to date in SiGe technology (see Table I), and is comparable to the best published results for III–V *Ka*-band VCOs (see Table II).

B. Frequency Tuning

The oscillation frequency of the VCO is tuned through the control voltage applied to the varactors. The measured oscillation frequency of the VCO operating on 2.5 V with respect to the tuning voltage is shown in Fig. 12. A straight line is plotted overlapping the measured data to investigate the frequency-tuning linearity. The linear oscillation frequency ranges from 33.1 to 32.4 GHz for the tuning voltage from 0 to 1.5 V with the tuning constant of -0.547 GHz/V. As the tuning voltage goes higher than 1.5 V, the capacitance of the varactor diodes increases dramatically and the oscillation frequency rolls off from the linear regime. The phase noise, measured at 1-MHz frequency offset

Fig. 13. Signal power and phase noise of the SiGe VCO with respect to the frequency-control voltage from 0 to 2.5 V at a fixed 2.5-V supply voltage. The phase noise is measured at 1-MHz frequency offset from the oscillating frequency.

from the oscillation frequency, and signal power of the VCO with respect to the control voltage are shown in Fig. 13. The phase noise varies from -90 to -100 dBc/Hz throughout the whole tuning range. The signal power variation in the linear frequency tuning regime ($V_{\text{control}} = 0 - 1.5$ V) is from -13.2 to -14.4 dBm.

C. Frequency Pushing and Bias Effects

VCOs are well known to be subject to frequency pushing. The frequency deviation of the VCO because of the supply voltage variation is shown in Fig. 14. For a supply voltage change from 2.5 to 1.6 V, the overall frequency drift of the VCO is approximately 0.45 GHz. The signal power and phase noise variation with respect to the supply voltage are shown in Fig. 15. The signal power improves as the supply voltage increases because of larger swing headroom. The phase noise, at 1-MHz frequency offset, moves up and down from -90 to -100 dBc/Hz throughout the operational voltage range.

The characteristics of the VCO operating on 2.5 V with different bias currents are shown in Figs. 16 and 17, respectively. The oscillation frequency is practically constant for low bias conditions, but rolls off for high bias conditions. Under high bias conditions, the incremental voltage drop across the base-emitter

Fig. 14. Oscillation frequency variation of the SiGe VCO with respect to supply voltage change from 1.6 to 2.5 V.

Fig. 15. Signal power and phase noise of the SiGe VCO with respect to supply voltage change from 1.6 to 2.5 V. The phase noise is measured at 1-MHz frequency offset from the oscillating frequency.

Fig. 16. Oscillation frequency variation of the SiGe VCO with respect to quiescent bias current at a fixed 2.5-V supply voltage.

Fig. 17. Signal power and phase noise of the SiGe VCO with respect to quiescent bias current at a fixed 2.5-V supply voltage. The phase noise is measured at 1-MHz frequency offset from the oscillating frequency.

junctions of the transistors leads to the rapid increase of the diffusion capacitance. The excess junction capacitance is added to the VCO circuit and, consequently, lowers the oscillation frequency. The signal power of the VCO increases as the bias quiescent current increases and becomes saturated in the high bias regime. The phase noise becomes worse under high bias conditions. When the signal power reaches saturation, the gain of the signal power from high bias currents is no longer able to compensate for the high excess and low-frequency noise under high bias conditions.

VI. SUMMARY

A low-power fully integrated differential Ka -band VCO is implemented in the raised extrinsic base 200-GHz SiGe HBT technology. Line inductors instead of transmission lines are demonstrated to be feasible for use in the resonators for Ka -band applications. This SiGe VCO oscillates at 33 GHz on 1.6–2.5-V supply voltage, consumes a minimum power of 2.64 mW, and delivers an SSB phase noise of -99 dBc/Hz at 1-MHz frequency offset. This SiGe VCO achieves a FOM of -183.7 dBc/Hz, which is comparable to the best published Ka -band VCOs in any semiconductor technology.

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