An Inductorless Ka-Band SiGe HBT Ring Oscillator

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***Abstract*—An inductorless Ka-band silicon–germanium (SiGe) heterojunction bipolar transistor (HBT) ring oscillator is presented. The Ka-band operation is achieved with the addition of a cross-coupled pair to the simple differential inverting amplifier of a single-stage ring oscillator. Implemented with 120-GHz SiGe HBTs, the circuit occupies an extremely compact active area of only 0.0108 mm^2 due to lack of inductors. The frequency is tunable from 28.36 to 31.96 GHz, and the single-sideband phase noise is −85.33 dBc/Hz at 1-MHz offset from 31.96 GHz. Operating on a −3-V supply, the total power consumption is 87 mW. The resulting oscillator figure-of-merit is −156 dBc/Hz. To our knowledge, this oscillator achieves the best figure-of-merit while occupying the least active area, when compared with other state-of-the-art inductorless ring oscillators operating over a similar frequency range.**

***Index Terms*—Heterojunction bipolar transistor (HBT), inductorless, Ka-band, ring oscillator, silicon–germanium (SiGe).**

I. Introduction

DUE to their design simplicity, inherent multiphase output, wide frequency tuning capability, compact size, and ease of integration, ring oscillators are now essential building blocks in high-speed digital and optical communication systems. In spite of this, ring oscillators have yet to find many applications in the millimeter-wave (millimeter-wave $\geq$30 GHz) range because of the high frequency and stringent phase noise requirements. Hence, oscillators for millimeter-wave applications have traditionally been implemented as harmonic oscillators using an LC tank with a high-quality factor (Q) as the resonator. However, with the large area required for inductors, the limited frequency tuning range of LC oscillators, and the trend toward very large scale integration (VLSI), inductorless ring oscillators remain logical alternatives. Research into high-performance devices and novel circuit topologies to overcome the limitations of inductorless ring oscillators has yielded several designs with high operating frequency [1]–[4]. Still, the proposed oscillators [1]–[4] are limited only to K-band operation.

This letter presents the implementation of an inductorless ring oscillator capable of Ka-band operation using 120-GHz silicon–germanium (SiGe) heterojunction bipolar transistors (HBTs) [5]. The circuit, optimized for high-frequency operation, low power consumption, and ultra-compact size, demonstrates the potential of inductorless ring oscillators for monolithic millimeter-wave applications.

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II. Circuit Design

A ring oscillator is realized by connecting an odd number of single-ended inverting amplifiers in a feedback loop, thus forming a ring structure. The open-loop transfer function of a ring oscillator is given as

$$H(j\omega) = [A(j\omega)]^N \tag{1}$$

where $A(j\omega)$ is the transfer function of an inverting amplifier and N is the number of amplifier stages. For a ring oscillator to begin oscillation, the open-loop gain must be greater than unity when the total phase shift around the loop is multiples of 2π radians. Each inverting amplifier contributes a static dc phase shift of π radians, resulting in net π radians for odd stages. Hence, the inverting amplifiers themselves must then contribute the other π radians of frequency-dependent ac phase shift required. These conditions, known as the Barkhausen criteria, are

$$|H(j\omega)| > 1 \tag{2}$$

and

$$\arg[H(j\omega)] = \pi. \tag{3}$$

With differential inverting amplifiers, an even number of stages can be used. The static dc phase shift required can be achieved by simply interchanging the outputs of one inverting amplifier.

In time domain, the oscillation frequency of a ring oscillator is determined by the delay associated with the charging and discharging of parasitic capacitors. Thus, the oscillation frequency is given by

$$f_{\rm osc} = \frac{1}{2NT} \tag{4}$$

where N is the number of amplifier stages, and T is the delay through each stage. The extra factor of two in the denominator is due to the fact that the signal must propagate twice around the loop to obtain one full period. According to (4), the $f_{\rm osc}$ of a ring oscillator can be increased by reducing N. If N is reduced by a factor of two, the oscillator can potentially operate at twice the frequency, in addition to dissipating only half the power. Phase noise also decreases as N is reduced in a differential ring oscillator [6]. In contrast, the frequency-dependent ac phase shift contributed by each stage is now doubled. As N is further reduced, it becomes increasingly more difficult

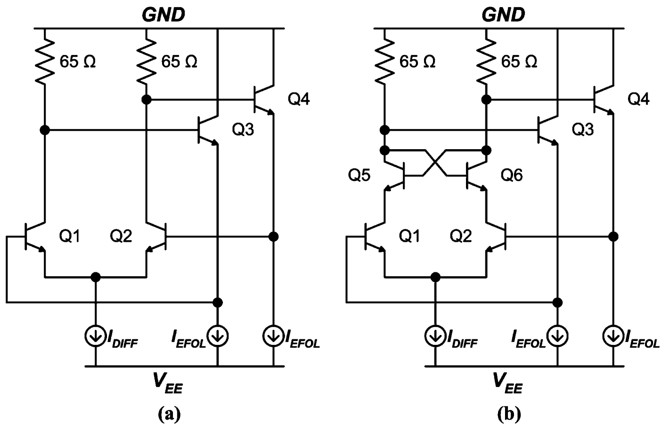

Fig. 1. (a) Schematic of a simple differential inverting amplifier core that fails to oscillate, and (b) schematic of the present modified differential inverting amplifier core that oscillates. Emitter area of Q_1–Q_2 and Q_5–Q_6 is $0.2 \times 5\ \mu m^2$; emitter area of Q_3–Q_4 is $0.2 \times 6\ \mu m^2$.

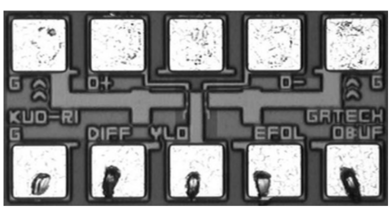

Fig. 2. Chip micrograph of the inductorless Ka-band SiGe HBT ring oscillator.

to maintain sufficient frequency-dependent ac phase shift before the open-loop gain drops to less than unity. For the limiting case where $N = 1$, that single-stage must provide the whole π radians of frequency-dependent ac phase shift while still maintaining an open-loop gain of greater than unity.

Consider a single-stage SiGe HBT ring oscillator core composed of a simple differential inverting amplifier with its outputs fed back to its inputs of the opposite polarity, as shown in Fig. 1(a). Simulations indicate that this oscillator will not oscillate because the Barkhausen criteria are not satisfied. Several improvements to the circuit in Fig. 1(a) have been proposed to improve the phase condition of the inverting amplifier, by adding poles to increase the delay around the loop [2], [4], [7]. The differential inverting amplifier core used in the present oscillator design is shown in Fig. 1(b). It is a modified version of that found in [7]. A cross-coupled pair (Q_5 and Q_6) added on top of the differential pair (Q_1 and Q_2) provides positive feedback to increase phase shifting [7], [8]. Open-loop simulations indicate π radians of frequency-dependent ac phase shift occur at about 35 GHz, while the small-signal gain is 4.5 dB. Hence, the Barkhausen criteria are satisfied enabling oscillations to build up. Transient simulations are in agreement and show the oscillator stabilizing to about 32 GHz.

The advantages of using only one cross-coupled pair, in the present work, as opposed to the two proposed in [7], are as follows. One cross-coupled pair suffices in improving the phase condition for oscillation with these SiGe HBTs. The use of the second cross-coupled pair would result in extra delay and reduce the maximum achievable f_{osc}. In addition, an increase of one V_{be_on} in the supply is needed to accommodate the addition of the second cross-coupled pair, resulting in extra unwanted power dissipation.

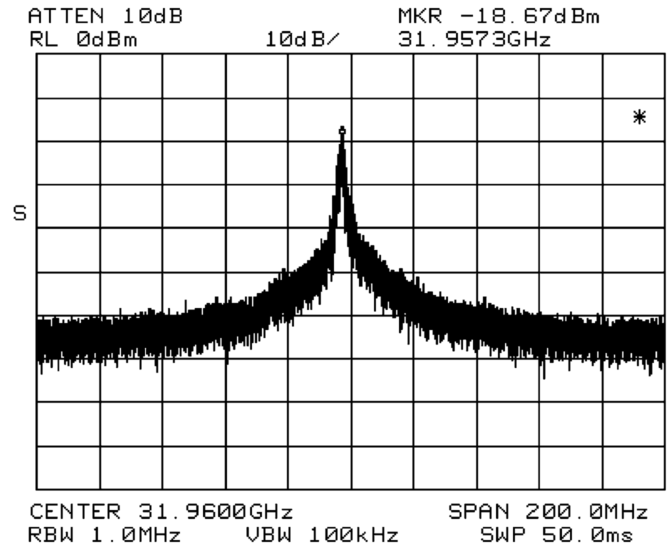

Fig. 3. Measured output power spectrum of the Ka-band ring oscillator operating at 31.96 GHz.

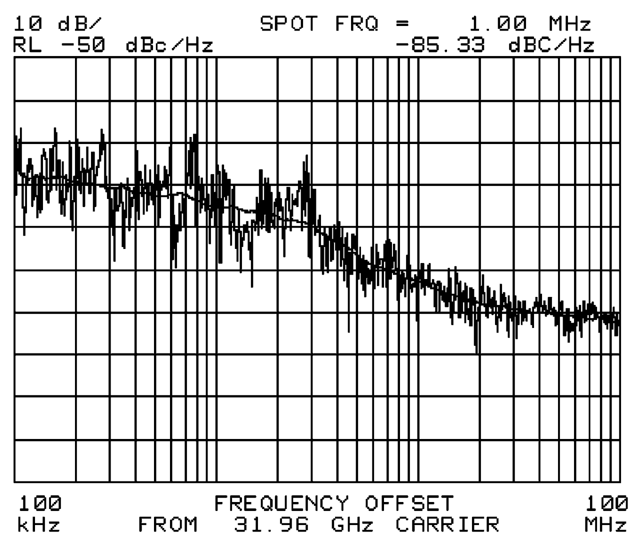

Fig. 4. Measured phase noise of the Ka-band ring oscillator operating at 31.96 GHz.

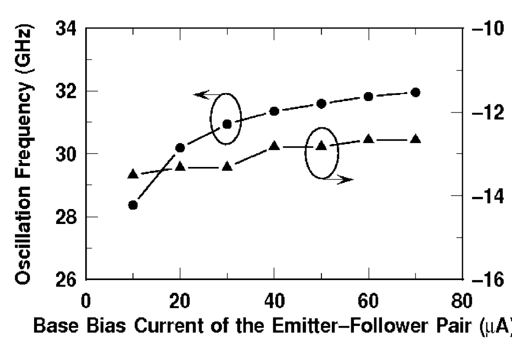

Fig. 5. Measured oscillation frequency and calibrated output power versus the base bias current of the emitter–follower pair.

TABLE I
FIGURE-OF-MERIT COMPARISON TO STATE-OF-THE-ART INDUCTORLESS RING OSCILLATORS OPERATING OVER A SIMILAR FREQUENCY RANGE

Reference	L [dBc/Hz]	f_m [MHz]	f_{osc} [GHz]	P_{diss} [mW]	FOM [dBc/Hz]	Process/f_T [-/GHz]	Active Area [mm^2]
This work	-85.33	1	31.96	87	-156.03	SiGe/120	0.0108
[1]	-85.00	1	26.60	250	-149.52	InP/53	--
[2]	-87.67	1	25.18	240	-151.89	SiGe/45	0.0225
[3]	-83.33	1	21.18	152	-148.03	SiGe/120	0.0180
[4]	-90.00	1	18.69	130	-154.29	InP/100	0.1972

III. RESULTS

The layout of the inductorless Ka-band SiGe HBT ring oscillator is done in a symmetrical fashion to minimize the effect of common-mode noise. The circuit occupies an extremely compact active area of less than $60 \times 180\ \mu\text{m}^2$. The total chip size, including bondpads, is only $380 \times 730\ \mu\text{m}^2$, as shown in Fig. 2.

The oscillator is tested on-wafer in a RF shield room using 40-GHz probes and cables. Custom-built filters are placed on the dc supplies to reduce the impact of supply noise. The oscillator is characterized with one output connected to a spectrum analyzer while the other output is terminated with 50 Ω through an equal length cable for symmetry. The measured loss of the connection from the spectrum analyzer to the oscillator of 6 dB is used to calibrate the measured signal power. The oscillator operates on a single supply of -3.0 V and consumes, including output buffers, only 87 mW. The output spectrum of the oscillator operating at 31.96 GHz with a measured signal power of -18.67 dBm is shown in Fig. 3. At that frequency, the measured single-sideband (SSB) phase noise is -85.33 dBc/Hz at 1-MHz offset, as shown in Fig. 4. The f_{osc} is tuned through the base bias current of the emitter–follower pair. A decrease in the emitter-follower tail current decreases the cutoff frequency (f_T) and the charge current of the parasitic capacitances, hence decreasing the f_{osc} [4]. The measured f_{osc} as a function of base bias current, as shown in Fig. 5, ranges from 28.36 to 31.96 GHz, resulting in a 12% tuning range around the mid-band frequency. Adjusting the base bias current of the emitter-followers also affects the output signal power. The calibrated (measured + loss) output power as function of base bias current, as shown again in Fig. 5, ranges from -13.50 to -12.67 dBm. Less than 1 dB of output power variation is achieved when the frequency is tuned.

Numerous ring oscillators have been published. To compare the performance of the present work with other state-of-the-art inductorless ring oscillators operating over a similar frequency range, the oscillator figure-of-merit is determined according to

$$\text{FOM} = L(f_m) - 20\log\frac{f_{\text{osc}}}{f_m} + 10\log\frac{P_{\text{diss}}}{1\text{mW}} \quad (5)$$

where L is the phase noise, f_m is the offset frequency, and P_{diss} is the dissipated power. The comparison with other literature reports is given in Table I. The present oscillator achieves a FOM of -156 dBc/Hz, which is the best achieved to date, due to an increase in f_{osc} and a reduction in P_{diss}, as well as occupying the smallest active area.

IV. CONCLUSION

An inductorless Ka-band SiGe HBT ring oscillator optimized for high-frequency operation, low power consumption, and ultra-compact size has been realized with an addition of a cross-coupled pair to the simple differential inverting amplifier. The circuit demonstrates the potential of inductorless ring oscillators for emerging monolithic millimeter-wave applications.

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