SiGe Integrated mm-Wave Push-Push VCOs with Reduced Power Consumption

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***Abstract*— For use in automotive radar applications we have designed and fabricated several push-push VCOs within the frequency range 67 to 75 GHz. In this paper we present one of these oscillators which can be tuned from 71.3 GHz to 75.8 GHz. In this tuning range the measured output power is 3.5 ± 0.4 dBm with an DC to RF efficiency $\eta = 1.6\,\%$. The measured single sideband phase noise is below −105 dBc/Hz at 1 MHz offset frequency. With a reduced supply voltage the efficiency can be increased to $\eta = 3.5\,\%$ with an RF output power of 1.5 dBm. The circuits are fabricated in a production-near SiGe:C bipolar technology. The SiGe:C bipolar transistors show a maximum transit frequency $f_T = 200$ GHz and a maximum frequency of oscillation $f_{max} = 275$ GHz. For the passive circuitry transmission-line components, MIM-capacitors and integrated resistors are used.**

I. Introduction

In future millimeter-wave and submillimeter-wave applications as high-resolution radars, biological and chemical sensors or wide bandwidth communication systems the key components are compact, reliable low noise sources [1]. Recent advances in SiGe HBTs [2] have increased the usable frequency range of SiGe devices in the past years. This allows SiGe to compete now with III/V semiconductor based technologies at millimeter-wave frequencies.

The low noise level at low frequencies (LF) and the resulting low oscillator phase noise are areas in which SiGe HBTs generally outperform III/V HBTs or HEMTs [3]. The significant lower costs of SiGe chip area can reduce the prices of millimeter-wave systems and thus it has the potential to open mass markets for consumer systems at millimeter-wave and submillimeter-wave frequencies.

Fig. 1 shows the state-of-the-art output power and measured single side band phase noise level of integrated oscillators for signals from 40 GHz to 100 GHz. [11], [16] are push-push oscillators and [4]–[10], [12]–[15], [17] are fundamental frequency oscillators. In [4], [10], [13], [15], [17] output buffers are used. Compared with oscillators realized in the same frequency range the device presented here shows an superior phase noise level.

II. The Push-Push Oscillator Principle

A push-push oscillator consists of two symmetric suboscillators operating in odd mode at the fundamental frequency f_0. Nonlinear distortion in the suboscillators cause harmonic frequency contributions at the nth harmonic $f_n = (n+1)\,f_0$. At the common output port the output signals are added up. Due to the phase differences of the fundamental frequency signal and the even harmonics, these frequency contributions cancel out, while the odd harmonics add in phase. Hence, power is delivered to the load only at the odd harmonics $f_1, f_3, \ldots$ [11], [18]–[20].

In a push-push oscillator the fundamental frequency is not damped by the oscillators load impedance because in odd mode operation a ‘virtual ground’ exists at the common output port. Therefore in a push-push oscillator the loaded Q-factor is equal to the unloaded Q-factor. As the two suboscillators operate at halve of the output frequency, at this oscillation

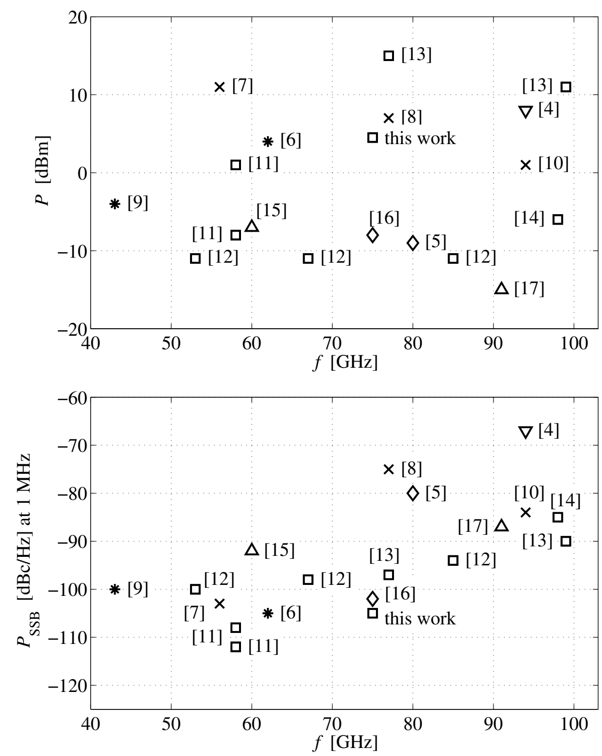

Fig. 1. State-of-the-art output power P and single side band phase noise level P_{SSB} for integrated oscillators (□ SiGe HBT, ◇ GaAs HBT, ✱ InP HBT, × GaAs HEMT, ▽ GaAs HFET and △ CMOS).

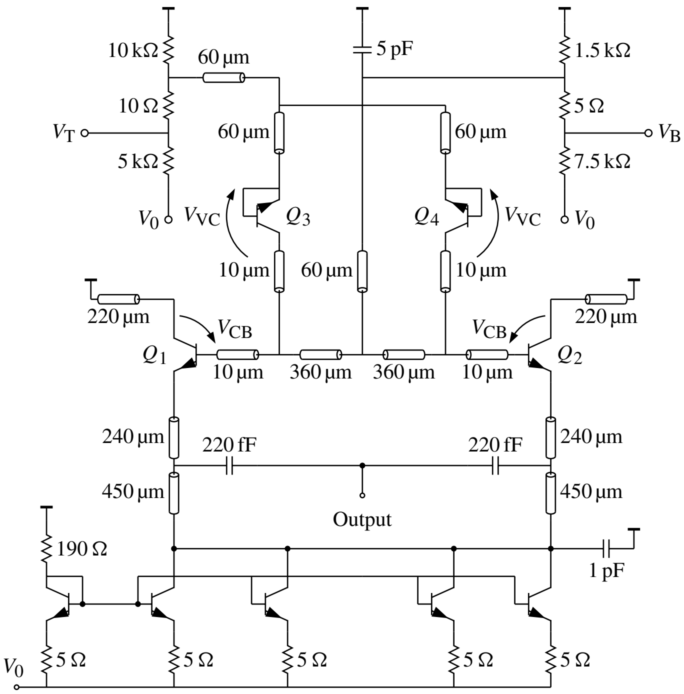

Fig. 2. Circuit diagram of the push-push oscillator

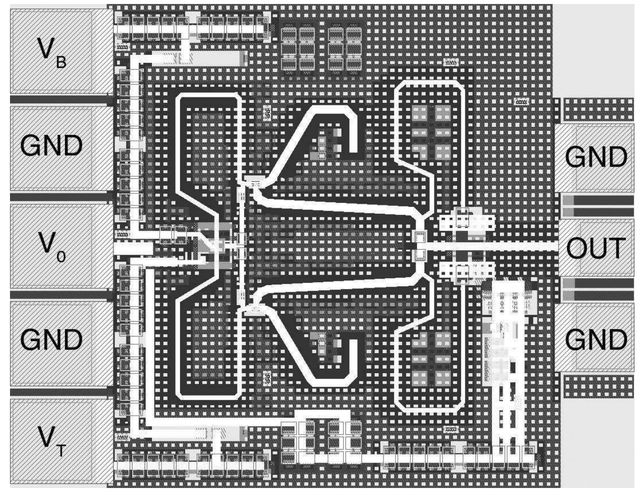

Fig. 3. Layout of the push-push oscillator (800 µm × 620 µm)

frequency higher resonator Q-factors are available. Compared to solutions using frequency doublers, a push-push oscillator is generally less space consuming and offers a lower phase noise level. Additionally push-push oscillators are highly resistant to load pulling effects, because the suboscillators are terminated by 'virtual ground' and only the first harmonic frequency component is influenced by the oscillators load impedance. The temperature sensitivity of a push-push oscillator is generally a lower compared to a fundamental frequency oscillator because of the halved oscillation frequency.

III. Circuit Design

In the circuit design we first consider one single suboscillator and the start-up conditions in the small signal case. By connecting an inductive load to the base terminal, the active device gets instable. In order to fulfill the oscillation condition at the desired frequency $f_0 = 37.5\,\text{GHz}$ a capacitive loading at the emitter terminal and an inductive loading at the collector terminal needs to be connected.

The two suboscillators can generally be coupled either via the collector, the base or the emitter network to perform the 180° phase locking and to realize the superposition of the output signals with counterphase fundamental waves. A harmonic balance analysis of these three types of design shows best results for coupling via the emitter networks. This agrees with the designs in [21] and [20] where we realized hybrid fabricated and fully integrated push-push oscillators. In [20] we have used spiral inductors. In contrast, for the oscillator presented here the inductors are replaced by microstrip lines to obtain higher Q-values.

The circuit diagram of the whole oscillator with its bias network is presented in Fig. 2. The collector terminals are grounded via a transmission line resonators. At the emitter terminals 240 µm long transmission lines are connected. For the RF signal the ends of these lines are combined via capacitors to the common output port. For bias decoupling 450 µm long microstrip lines with a characteristic impedances $Z = 68\,\Omega$ providing an increased inductance per length are used.

At the base terminals 370 µm long microstrip lines serving as inductors are connected. At the connecting point of the base networks a virtual ground for the fundamental frequency signal at f_0 exists due to the odd mode operation. For the decoupling of the first harmonic signal at f_1 from the bias network a transmission line and a large capacitor are used.

The DC supply is accomplished by a constant emitter bias current impressed by a current mirror and a fixed DC voltage at the base terminal. The RF short connected at the base network and the impressed emitter current allow to exceed the breakdown voltage $V_{B,CE} = 1.7\,\text{V}$ of the active devices [22]. Using 4 branches for the current source, the current in the reference path is only one quarter of sum of the emitter currents in Q_1 and Q_2. Thus the power dissipation in the reference path is reduced. The DC supply voltage at the base terminal is accomplished by a resistive divider. By varying the voltage V_B the collector to base voltage V_{CB} can be tuned.

In order to allow tuning of the oscillation frequency two varactors are placed at the base networks of both suboscillators. For this purpose we employ the capacitance of a collector-base junction as a varactor element. The 60 µm long microstrip line at the base/emitter terminal of the varactor increases the tuning range of the VCO. The voltage V_{VC} denotes the voltage at the collector-base junction of the varactor. This voltage can be adjusted by the external tuning voltage V_T.

A nonlinear circuit simulation was performed using the

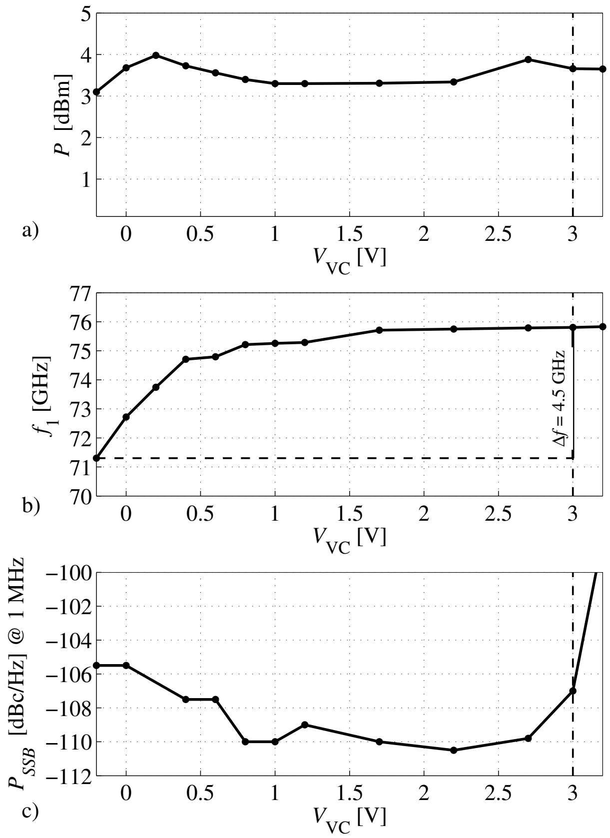

Fig. 4. Measured a) output power P, b) output frequency f_1 and c) single side band phase noise P_{SSB} at 1 MHz offset from the carrier on the varactor voltage V_{VC} ($V_0 = -3.0\,V$, $V_B = -1.8\,V$)

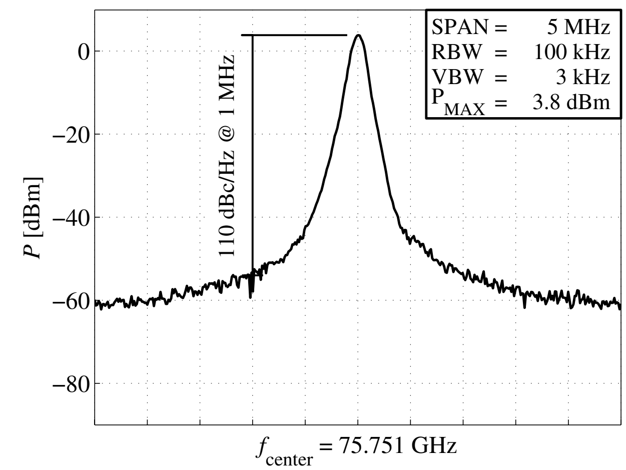

Fig. 5. Measured spectrum at the first harmonic frequency of the oscillator signal for $V_0 = -3.0\,V$, $V_B = -1.8\,V$ and $V_T = -4.5\,V$ ($V_{VC} = 2.6\,V$)

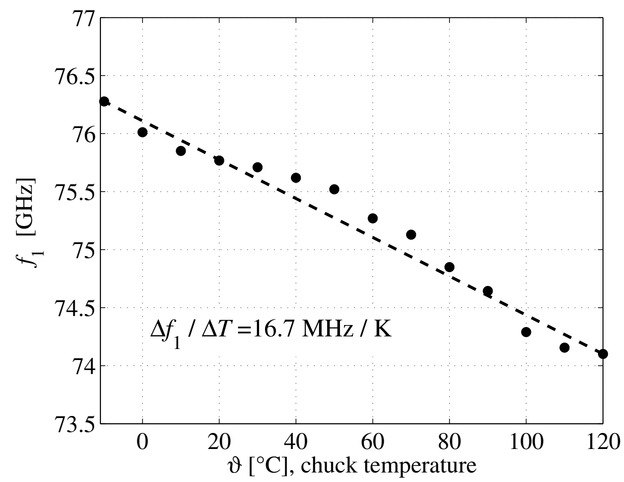

Fig. 6. Measured temperature sensitivity of the output frequency f_1 for $V_0 = -3.0\,V$, $V_B = -1.8\,V$ and $V_T = -4.5\,V$ ($V_{VC} = 2.6\,V$)

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IV. EXPERIMENTAL RESULTS

The push-push oscillator has been fabricated in a production-near SiGe:C bipolar technology of INFINEON TECHNOLOGIES [2]. The transistors make use of a double-polysilicon self-aligned emitter-base configuration. The effective minimum emitter width is 0.14 µm. The maximum transit frequency f_T is 200 GHz and the maximum frequency of oscillation f_{max} is 275 GHz. The transistors actually used in this work have two emitter fingers, each 10 µm long. The process additionally offers a four-layer copper metallization with intermediate SiO_2 isolation, two types of polysilicon resistors, TaN resistors and MIM-capacitors. The layout of the fabricated circuit is depicted in Fig. 3.

The output signal of the push-push oscillator is measured on chip by an HP 71000 spectrum analyzer using appropriate harmonic mixer. The measured power levels are corrected for the conversation loss of the mixers. A W-band power meter is used to verify the output power level. Losses of the RF-probe and the measurement cables are taken into account with 1 dB. For the DC voltage supply the chip was mounted on a FR4 substrate. By a combination of electrolyte and ceramic capacitors the supply voltages are stabilized. The chip is connected to the substrate by wire bonding.

Fig. 4 demonstrates the performance of the oscillator as a function of the varactor voltage V_{VC} that is adjusted by the tuning voltage V_T. The bias voltage V_0 was set to $-3.0\,V$ and the base tuning voltage V_B to $-1.8\,V$. Thus the collector to base voltages of the transistors Q_1 and Q_2 are $V_{CB} = 1.8\,V$ and the emitter currents in each of these devices are 20 mA.

The oscillator output frequency can be tuned from 71.3 GHz to 75.8 GHz (6.1 %). In this frequency range the output power is 3.5 ± 0.4 dBm. The measured single sideband phase noise level at 1 MHz offset frequency is less than -105 dBc/Hz. At a varactor voltage $V_{VC} = 2.2\,V$ a record value of -110 dBc/Hz is measured. The measured spectrum of the oscillator output signal for this varactor voltage is depicted in Fig. 5.

The measured power of the fundamental frequency signal at

TABLE I

EFFICIENCY OF THE OSCILLATOR VERSUS SUPPLY VOLTAGE ($-V_T = 4\,V$)

$-V_0$	1.8 V	2.4 V	3.0 V	3.6 V
$-V_B$	0.8 V	1.4 V	2.0 V	2.2 V
f_1	76.16 GHz	76.21 GHz	76.12 GHz	75.18 GHz
P_{RF}	1.5 dBm	3.8 dBm	3.9 dBm	1.0 dBm
P_{SSB} @ 1 MHz	−107 dBc	−109 dBc	−110 dBc	−108 dBc
$\eta = P_{RF}/P_{DC}$	3.5 %	2.7 %	1.6 %	0.52 %

f_0 is -27.1 dBm. The low power level of this signal indicates a high symmetry of the fabricated push-push oscillator and a proper odd mode operation. In the whole tuning range of the VCO the measured fundamental frequency output power is below -25.5 dBm.

For measuring the temperature sensitivity of the oscillator the chuck temperature is modified. As can be seen in Fig. 6 the temperature sensitivity of the VCO is -16.7 MHz/K. We propose that this low temperature sensitivity is a result of the lower temperature dependency of the transistors at the halved oscillation frequency compared to a fundamental frequency oscillator. At $\vartheta = 120°C$ the phase noise level is increased from -110 dBc/Hz to -107 dBc/Hz.

The power consumption of the whole circuit at the bias point $V_0 = -3.0\,V$, $V_B = -2.0\,V$ is 140 mW. By reducing the supply voltage V_0 and the base tuning voltage V_B simultaneously, the output power P decreases but the DC to RF efficiency η increases. As given in Table I an efficiency $\eta = 3.5\,\%$ is achieved with $V_0 = -1.8\,V$.

V. CONCLUSION

A push-push VCO with a low power consumption and a tunable output frequency form 71.3 GHz to 75.8 GHz has been presented. This result complies with a relative tuning bandwidth of 6.1 %. The maximum output power is 3.5 ± 0.4 dBm and the single side band phase noise is less than -105 dBc/Hz at an offset frequency of 1 MHz.

VI. ACKNOWLEDGEMENT

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