

A Fully Integrated SiGe Low Phase Noise Push-Push VCO for 82 GHz

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Abstract— We present a fully monolithically integrated push-push oscillator fabricated in a production-near SiGe:C bipolar technology. The oscillator output frequency can be varactor tuned from 80.6 GHz to 82.4 GHz. In this frequency range the measured output power is 3.5 ± 0.4 dBm while the measured single sideband phase noise is less than -105 dBc/Hz at 1 MHz offset frequency. To our knowledge this phase noise level is the lowest one reported in literature so far for an VCO in this frequency band. The transistors used in this work 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

The availability of suitable signal sources is a precondition for the application of SiGe technology in millimeter wave systems [1]. Compared to III/V based technologies SiGe integrated circuits can open up mass markets for millimeter wave systems due to the significant lower costs. Using enhanced circuit concepts as the push-push topology allows to reach a maximum in performance with a given technology.

In combination with passive components realizable in monolithically integrated oscillators for millimeter wave frequencies are feasible today. One of the key requirements for an oscillator in applications as e. g. automotive radars and optical communication systems is to provide a low phase noise level.

The push-push oscillator principle is well suited for designing low phase noise oscillators. Here, two subcircuits oscillate at the fundamental frequency f_0 , while only the first harmonic at $f_1 = 2f_0$ is coupled to the output port [2], [3]. As the two suboscillators oscillate at half of the output frequency, at this oscillation frequency higher resonator Q -factors are available. Furthermore, the fundamental frequency signal in a push-push oscillator is terminated by a ‘virtual ground’. Thus, the loaded Q -factor is equal to the unloaded Q -factor of the oscillator.

The push-push oscillator principle allows to extend the usable frequency range of an active device for the realization of stable signal sources [4]. Compared to solutions using frequency doublers, a push-push oscillator is generally less space consuming and offers a lower phase noise level [5]. Additionally push-push oscillators are highly resistant to load pulling effects, because the

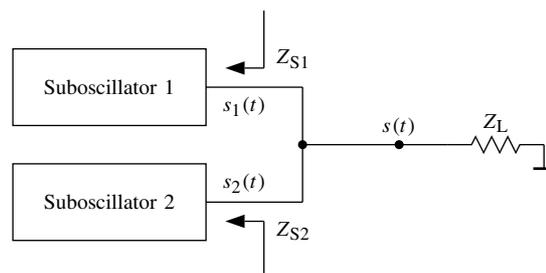


Fig. 1. The push-push oscillator principle

suboscillators are terminated by virtual grounds and only the first harmonic frequency component is influenced by the oscillators load impedance.

II. THE PUSH-PUSH OSCILLATOR PRINCIPLE

A push-push oscillator consists of two symmetric, individual suboscillators (Fig. 1) operating 180° out of phase at half of the output frequency. The generated signals of the two suboscillators are given by

$$s_1(t) = \sum_{n=0}^{\infty} a_n \cdot \sin(\omega_n t + \varphi_n) \quad (1)$$

$$s_2(t) = \sum_{n=0}^{\infty} a_n \cdot \sin(\omega_n t + \varphi_n + (n+1)\pi). \quad (2)$$

The spectral components have the same amplitudes a_n and differ only in phase by $(n+1) \cdot \pi$, while n is the harmonic index. The output signal is the sum of the two suboscillator signals

$$s(t) = \sum_{n=1,3,\dots}^{\infty} 2 \cdot a_n \cdot \sin(\omega_n t + \varphi_n). \quad (3)$$

Due to the phase differences of the fundamental frequency and the even harmonics, these frequency contributions cancel out, while the odd harmonics add in phase. Hence, in a proper operating push-push oscillator the power is delivered to the load only at the odd harmonics f_1, f_3, \dots . Efficient operation of the circuit is obtained, when both suboscillators operate at the same idling frequency f_0 and stable odd mode operation is ensured.

For the analysis of a push-push oscillator we cut the circuit at its symmetry line and investigate the odd mode and the even mode operation individually. In the odd mode equivalent circuit the suboscillator is terminated by a virtual ground. Thus, the small signal oscillation condition for one suboscillator in odd mode operation is given by

$$Z_S = 0. \quad (4)$$

The fundamental frequency is not attenuated by the oscillators load impedance due to the virtual ground in the odd mode. Therefore in a push-push oscillator the loaded Q -factor is equal to the unloaded Q -factor.

In the even mode equivalent circuit the suboscillator is terminated by twice the load impedance $2 \cdot Z_L$. Unwanted even-mode oscillations must be suppressed to ensure the stable odd-mode operation. This is unconditionally fulfilled, if

$$-2 \cdot \Re\{Z_L\} < \Re\{Z_S\}. \quad (5)$$

The load resistance attenuates the even mode signals and prevents any even mode oscillation. For the startup of oscillation in the odd mode the real part of the suboscillator input impedance $\Re\{Z_S\}$ needs to be less than zero. This can be summarized by the following start-up impedance condition for a push-push oscillator

$$-2 \cdot \Re\{Z_L\} < \Re\{Z_S\} < 0. \quad (6)$$

III. CIRCUIT DESIGN

In the circuit design we first consider one single suboscillator concerning the start-up conditions in the small signal case. By connecting an inductive load to the base terminal, the active device gets unstable. In order to fulfill the oscillation condition at the desired frequency $f_0 = 41$ GHz a capacitive loading at the emitter terminal and either a capacitive loading or 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 [6], [7] and [8] where we realized hybrid fabricated and fully integrated push-push oscillators. In [7] and [8] 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 terminal is grounded via a transmission line resonator. At the emitter terminals $190 \mu\text{m}$ long transmission lines are connected. For the RF signal the ends of these lines are combined with capacitors to the common output port. For the bias decoupling a $210 \mu\text{m}$ long microstrip line with a characteristic impedance $Z = 68 \Omega$ providing an increased inductance per length is used. At this transmission line

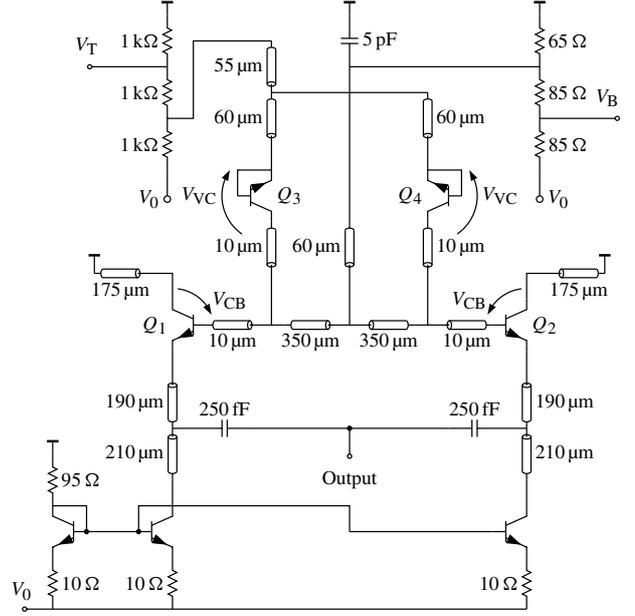


Fig. 2. Circuit diagram of the 82 GHz push-push VCO

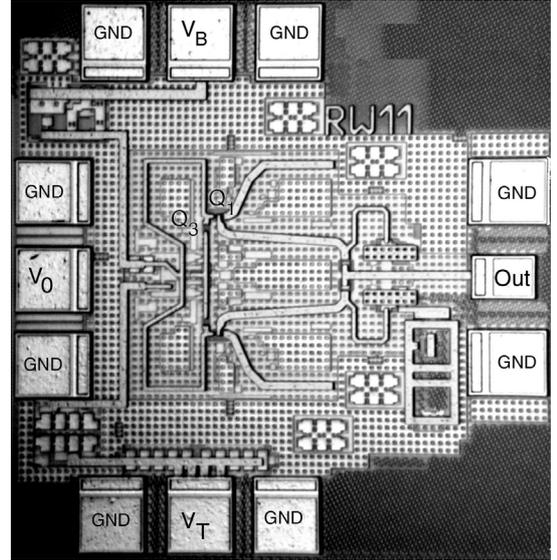


Fig. 3. Chip photograph of the 82 GHz push-push VCO ($700 \mu\text{m} \times 700 \mu\text{m}$)

a constant emitter bias current is impressed by a current mirror.

At the base terminals $350 \mu\text{m}$ long microstrip lines serving as an 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 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 a tuning of the oscillation frequency two varactors are placed at the base networks of both sub-oscillators. For this purpose we employ the capacitance

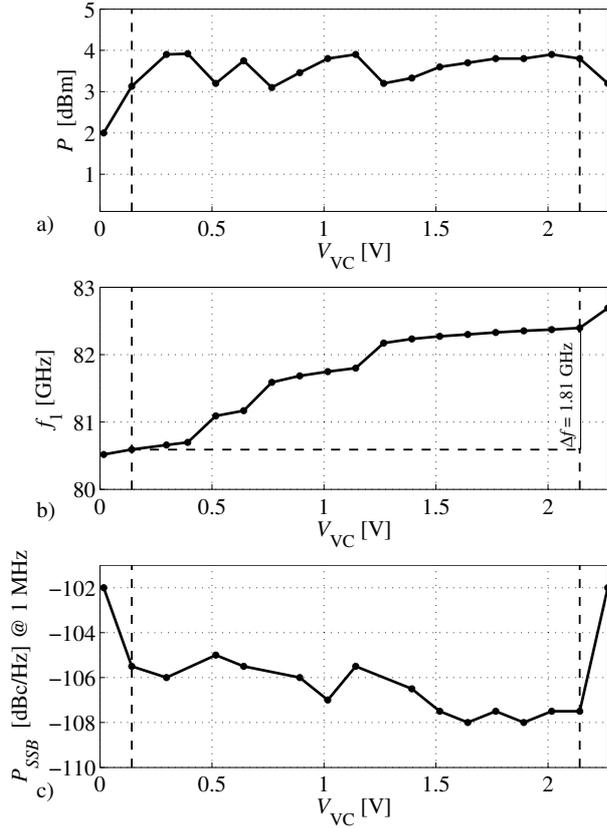


Fig. 4. Dependency of a) the output power P , b) the output frequency f_1 and c) the single side band phase noise P_{SSB} at 1 MHz offset from the carrier on the varactor voltage V_{VC} ($V_0 = -3.0$ V, $V_B = -4.0$ V)

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 Harmonic Balance tool in Agilent's ADVANCED DESIGN SYSTEM.

IV. EXPERIMENTAL RESULTS

The push-push oscillator has been fabricated in a production-near SiGe:C bipolar technology of INFINEON TECHNOLOGIES [9]. 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. A chip photograph 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 conversion loss of the mixers. A

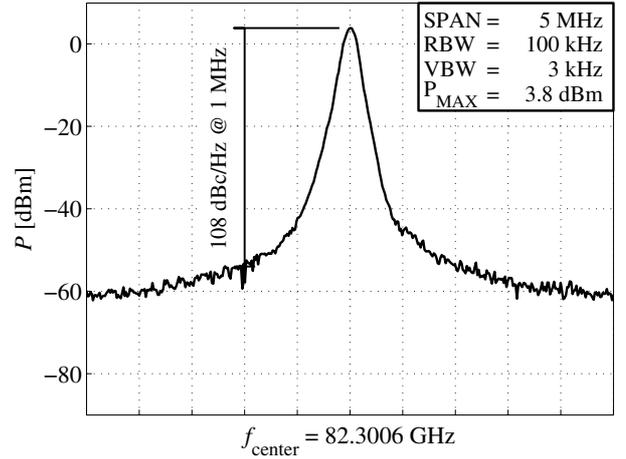


Fig. 5. Measured spectrum at the first harmonic frequency of the oscillator signal for $V_0 = -3.0$ V, $V_B = -4.0$ V and $V_T = -3.75$ V ($V_{VC} = 1.80$ V)

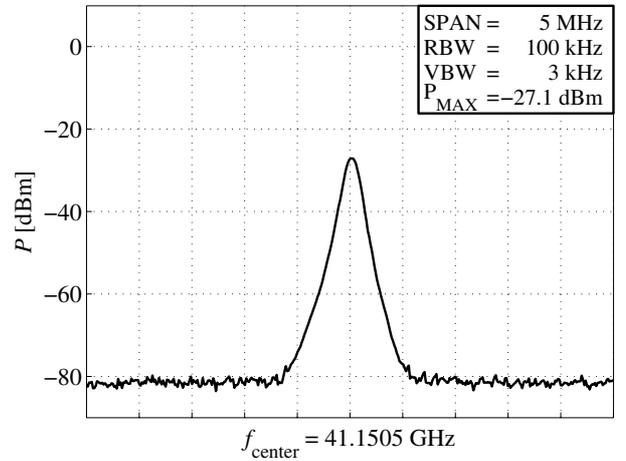


Fig. 6. Measured spectrum at the fundamental frequency of the oscillator signal for $V_0 = -3.0$ V, $V_B = -4.0$ V and $V_T = -3.75$ V ($V_{VC} = 1.80$ V)

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 -4.0 V. For this bias point the collector to base voltages of the transistors Q_1 and Q_2 are calculated to $V_{CB} = 1.7$ V and the emitter currents in each of these devices are 18 mA.

For a varactor voltage $V_{VC} = 2.05$ V the output power reaches its maximum of 3.9 dBm. The measured single side band phase noise level goes to its minimum of -108 dBc/Hz at an offset frequency of 1 MHz at a varactor voltage $V_{VC} = 1.80$ V. The measured spectrum of the oscillator output signal for this varactor voltage is depicted in Fig. 5. In this case the power consumption of

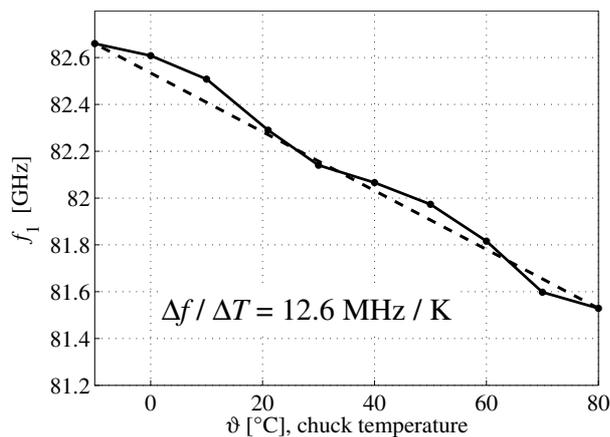


Fig. 7. Measured temperature sensitivity of the output frequency f_1 for $V_0 = -3.0$ V, $V_B = -4.0$ V and $V_T = -3.75$ V ($V_{VC} = 1.80$ V)

the whole device is 280 mW. The circuit has yet not been optimized for minimum power consumption.

Varying the varactor voltage between 0.1 V and 2.1 V the oscillation frequency changes from 80.6 GHz to 82.4 GHz, respectively. In this frequency range the oscillators output power is 3.5 ± 0.4 dBm and the measured single side band phase noise level is less than -105 dBc/Hz at an offset frequency of 1 MHz. This phase noise level is to our knowledge the lowest one reported for any monolithically integrated VCO in this frequency band.

The measured spectrum of the fundamental frequency f_0 is shown in Fig. 6. The low power level of this signal with -27.1 dBm 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 -26.5 dBm.

For measuring the temperature sensitivity of the oscillator the chuck temperature is modified. As can be seen in Fig. 7 the temperature sensitivity of the VCO is -12.6 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.

The measured performance was achieved by a single technological run without any redesign and without any tuning elements on chip. The output power of the circuit presented here can be increased by an integrated buffer amplifier for e. g. automotive radar applications as shown in [10].

V. CONCLUSION

A push-push VCO with a tunable output frequency from 80.6 GHz to 82.4 GHz has been presented. This result complies with a relative tuning bandwidth of 2.2%. The 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. To our knowledge this phase noise level is the lowest reported in literature so far for an integrated oscillator in this frequency band.

ACKNOWLEDGEMENT

The authors thank the *Bundesministerium für Bildung und Forschung* (BMBF), Germany, for financial support of SiGe technology development within the HiSpeed- and the KOKON-project.

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