SiGe-Based Circuits for Sensor Applications beyond 100 GHz

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***Abstract* — Key components of sensor front-ends have been realized for the frequency range beyond 100 GHz in a SiGe bipolar technology. The circuits presented include 110 GHz push-push and fundamental VCOs, both with up to 0 dBm output power, as well as fixed-frequency oscillators at 121 and 124 GHz. Furthermore, 122 GHz down-conversion mixers are demonstrated.**

***Index Terms* — SiGe, MMICs, millimeter-wave circuits, heterojunction bipolar transistors, voltage controlled oscillators, mixers.**

I. INTRODUCTION

Microwave and mm-wave radar sensors are used for the direct and indirect measurement of various parameters. Examples for directly measured parameters are velocity, distance, and angle, indirect parameters, among others, include vibration, revolution speed or material parameters. The fields of application include building and security technology, consumer goods, automotive equipment, as well as industrial technology. Such sensors offer advantageous features: They measure contactless, gathering several quantities and multiple targets simultaneously, measurement and assembly can be invisible (the sensor might be hidden behind a plastic cover) and applied in critical atmospheres (e.g., contaminated or explosive ones). Moreover, the sensors are to a large extent independent of weather conditions (especially fog and rain) or illumination.

The use of frequency bands in the upper mm-wave range beyond 100 GHz offers advantages with respect to antenna size. Also smaller chip size is achievable as distributed components within analog circuits scale inversely with frequency. Therefore, new technologies facilitating the realisation of key RF components for such high frequencies have to be evaluated.

Most of the above-described applications demand for low-cost realizations. Hence, moderate technology costs and a high level of integration is mandatory. A potential solution is the SiGe bipolar technology. Recent high-end processes offer heterojunction bipolar transistors (HBTs) with maximum transit and oscillation frequencies f_T and f_{max} beyond 200 GHz. These record values are combined with the known advantages of Si technology, e.g. high integration level, maturity of technology and good thermal behaviour.

In this work, a pre-production 0.13μm SiGe process from IBM is applied, which is based on an HBT with a transit frequency f_T in the 200 GHz range. The objective of this paper is to assess feasibility of the key sensor front-end functions, i.e., oscillator and mixer.

II. CIRCUIT DESIGN

To prove the suitability of the SiGe technology for applications in the frequency range beyond 100 GHz, the design and experimental results of two different oscillator concepts are presented, as well as a Gilbert-cell mixer and an anti-parallel diode pair harmonic mixer. All circuits target at the 122 GHz ISM frequency band.

A. Oscillators

The oscillator concepts investigated are a fundamental and a push-push design. In the past, oscillators with output frequencies beyond 100 GHz, have already been realized using the push-push principle, based on different semiconductor technologies, including SiGe [1]-[3]. Fundamental oscillators using SiGe HBTs have been demonstrated up to a frequency of 88 GHz [4].

The principle schematic of the fundamental oscillator is shown in Fig. 1. The circuit is designed in a thin-film microstrip environment using the top and bottom metallization layers of the backend-process of the technology to avoid substrate losses. The oscillation condition is established by a parallel connection of a quarter-wave short stub (Le1, Le2) and a junction varactor diode at the emitter. This results in a capacitive load and destabilizes the transistor together with small inductive loads at the base and the collector, realized by short sections of transmission lines.

The emitter load-configuration provides a large phase gradient to minimize the phase noise of the circuit. Power is coupled out by tapping at the quarter-wavelength line. By varying the tapping ratio, output power can be traded against lower phase noise, within certain limits. A second version of the oscillator is realized for a fixed frequency

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by replacing the varactor diode with an open-circuited stub.

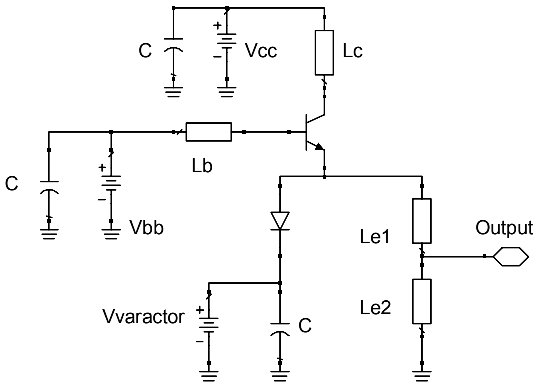

Fig. 1. Simplified schematic of fundamental oscillator.

The second design is based on the push-push principle. Fig. 2 provides a chip photograph of the circuit. The basic topology of a push-push oscillator consists of two circuits, oscillating in anti-phase at half of the desired output frequency. By combining the output, the fundamental signal cancels out and the 2nd harmonic signals add in-phase. The major advantages of the concept are that the usable frequency range of a device is extended and that each device is operating at half of the desired output frequency. This offers the possibility to employ larger size transistors which exhibit lower 1/f-noise due to a reduced current density [2]. Also, due to the higher gain margin at the lower frequency, the loaded Q can be increased, which results in phase-noise reduction.

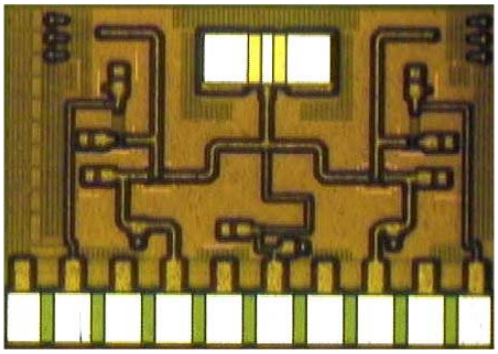

Fig. 2. Chip photograph of the push-push oscillator.

The push-push oscillator presented here is obtained by tuning the fundamental oscillator design described above to half the desired output frequency and mirroring the circuit at the base. The length of the resulting microstrip line connecting the bases of the two transistors is adjusted properly to ensure pure odd-mode oscillation. The push-push output is extracted directly at the symmetry point of the base-connecting microstrip line. The push-push oscillator is realized both as VCO and fixed-frequency type.

B. Mixers

Two mixer designs are presented, both optimized for applications in the 122 GHz ISM frequency band. The first mixer is based on the Gilbert-cell concept for a direct conversion receiver. Active mixers in bipolar technology using this concept have been reported in literature up to carrier frequencies of 42 GHz [5].

A chip photograph of the realized 122 GHz mixer is shown in Fig. 3. The circuit is designed for on-wafer testing, likewise the oscillator circuits described above. Balanced signals are provided for RF and LO by a Marchand-balun design based on the one presented in [6]. External biasing is provided by four sources connected via a DC probe to achieve maximum flexibility for the measurement. The balanced IF signal is coupled out via the DC probe as well in order to keep the number of required probes small. Due to the low-pass characteristic of the DC probe, the range of measurable intermediate frequencies is limited accordingly.

The second design is a sub-harmonic mixer based on an anti-parallel diode pair configuration, using the 6th harmonic of the LO. The circuit is usable for down-conversion of the source signal for frequency stabilization within a PLL. The diodes are realized by two HBT base-emitter junctions.

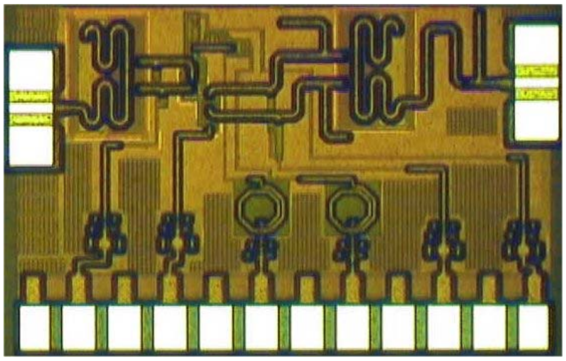

Fig. 3. Chip photograph of the Gilbert-cell mixer.

III. RESULTS AND DISCUSSION

A. Oscillators

The output spectra of the oscillators are measured with a 40 GHz spectrum analyzer, using an external F-band downconverter. The output is connected by means of WR-

08 waveguide probes. Figs. 4 and 5 present the power spectra of the fundamental and push-push fixed-frequency oscillators described in Sec. IIA. Taking into account the probe and waveguide losses of about 2.5 dB yields an output power of 1 dBm at 120.5 GHz for the fundamental and of -1.6 dBm at 124.2 GHz for the push-push oscillator. The bias conditions are I_C=25 mA for the fundamental and I_C=49 mA for the push-push oscillator, respectively, both at U_{CE}=1.7 V.

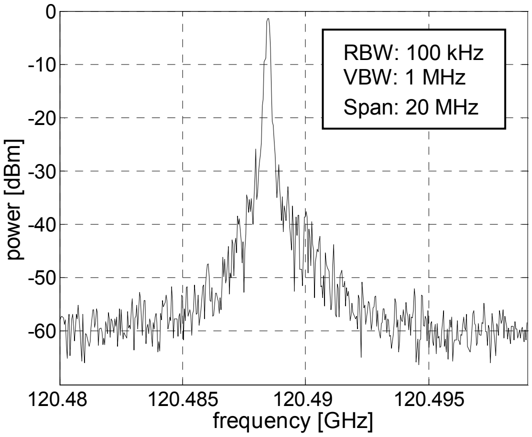

Fig. 4. Power spectrum of the fundamental fixed frequency oscillator (2.5 dB probe and waveguide losses not accounted for).

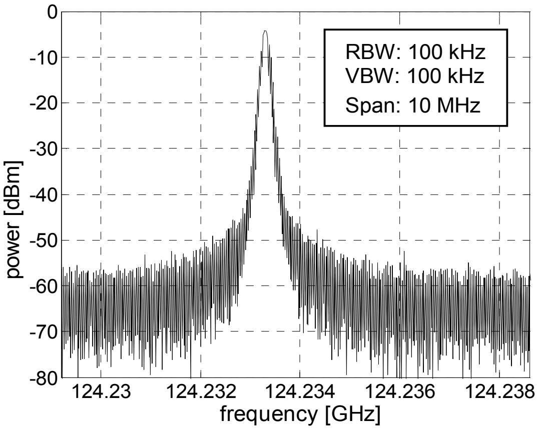

Fig. 5. Power spectrum of the push-push fixed frequency oscillator (2.5 dB probe and waveguide losses not accounted for).

Phase-noise performance at 1 MHz off-carrier can be estimated from the power spectrum to be less than -90 dBc/Hz for the fundamental and –97 dBc/Hz for the push-push-oscillator, respectively. These values are excellent. However, since there is no buffer separating the oscillator from the output, load-pulling could be an issue though we do not see indications for this in the tuning characteristics. The 7 dBc improvement of the push-push version over the fundamental one is significant. It is attributed to two main effects: First, one has an increased loaded Q at half of the output frequency due to the higher transistor gain available [2]. Second, noise is reduced due to oscillator coupling.

The tuning characteristics of both VCOs are depicted in Fig. 6. A wide tuning range of 8 GHz and 16 GHz (i.e., 7 and 14%) is achieved for the fundamental and push-push VCO, respectively. For both VCOs, measured frequency ranges are lower than predicted by simulations, which probably is caused by inaccuracies of the varactor diode model. This assumption is backed by the fact that the fixed-frequency oscillator results are in close agreement with the simulation.

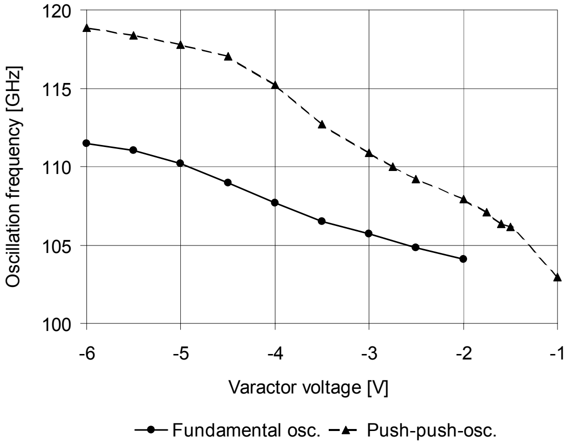

Fig. 6. Frequency vs. varactor voltage for the fundamental and push-push VCO.

From power-spectrum measurements, a phase-noise of -90 dBc/Hz at 1 MHz off-carrier is obtained for the push-push VCO. The fundamental VCO exhibits a drift so that meaningful phase-noise values could not be measured. The degradation of the phase-noise performance of the push-push VCO compared to the fixed-frequency type is attributed to the low varactor-diode Q factor.

In Fig. 7, output power is plotted as a function of oscillation frequency for both VCOs. A flat power characteristic around 0 dBm is achieved over a large portion of the respective tuning range. The power values of the push-push VCO for the frequencies between 110 and 120 GHz are drawn with symbols only because no calibration reference was available in this frequency range for the F-band mixer. Instead, the known conversion loss of the mixer for 122 GHz is assumed.

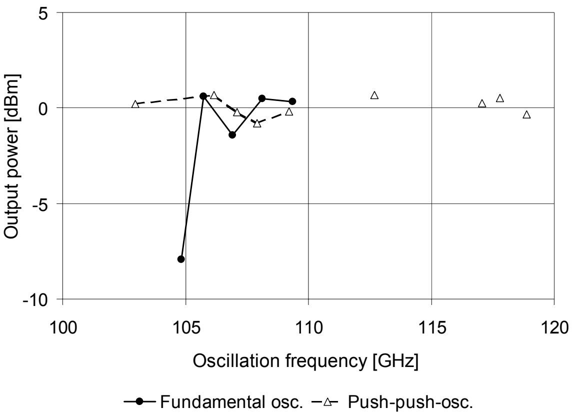

Fig. 7. Output power vs. oscillation frequency for the push-push and fundamental VCO (values above 110 GHz corrected by mixer conversion loss at 122 GHz, see text).

B. Mixers

The IF output of the 122 GHz Gilbert-cell down-conversion mixer is measured single-ended by means of a spectrum analyzer. As the IF output of the mixer is not buffered, an active probe (Agilent 41800A) with an input impedance of $100\,k\Omega$ is used to minimize the influence of the measurement probe on the mixer. For the LO, a PLL-stabilized Gunn oscillator with an output power of 0 dBm at 122 GHz is used.

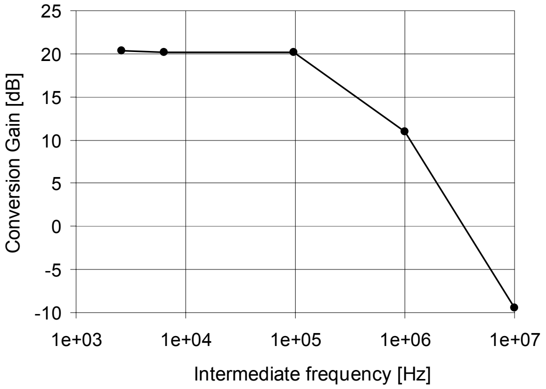

Fig. 8. Conversion gain vs. IF for the Gilbert-cell mixer (LO: -4 dBm @ 122 GHz; RF: -40dBm @ 122 GHz).

Fig. 8 shows conversion gain at an RF power of -40 dBm as a function of intermediate frequency. A single-ended conversion gain of 20 dB is achieved up to an IF of 100 kHz. This corresponds to an overall conversion gain of 23 dBm. As the IF signal is coupled out via the DC probe, the corner frequency of the conversion gain is determined by the low-pass DC-probe blocking capacitance and the high input impedance of the active probe.

For the sub-harmonic mixer with anti-parallel diode pair, a conversion loss of 20 dB is measured at 122 GHz, applying an LO power of 8 dBm at 20 GHz.

IV. CONCLUSIONS

Oscillators and mixers, the two key components of radar sensor front-ends for operation in the frequency range beyond 100 GHz were designed and realized employing an advanced SiGe bipolar process. Fundamental and push-push VCOs with a tuning range from 104-112 GHz and 102-118 GHz, respectively, and a flat output power of about 0 dBm are presented. Fixed-frequency fundamental and push-push oscillators achieve 1 dBm at 120.5 GHz and about –2 dBm at 124.2 GHz, exhibiting good phase-noise performance. Additionally, an active mixer at a frequency of 122 GHz based on the Gilbert-cell concept is demonstrated, which delivers 23 dB conversion gain, as well as a sub-harmonic mixer of order 6 using an anti-parallel diode configuration. It exhibits a conversion loss of 20 dB.

These results show that recent achievements in SiGe-HBT technology offer the potential of realizing highly integrated sensor front-ends even in the upper mm-wave frequency range.

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