A monolithic integrated 150 GHz SiGe HBT Push-Push VCO with simultaneous differential V-band output

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Abstract — **A fully integrated push-push voltage controlled oscillator (VCO) with simultaneous differential fundamental output is realized using an advanced 0.13µm SiGe HBT process. A maximum oscillation frequency of 155 GHz, up to –5 dBm output power at 150 GHz and 30 GHz wide tuning range is achieved. The measured phase-noise in the linear tuning range is around –85 dBc/Hz at 1 MHz offset from carrier. Up to +3 dBm output power and 6 dB lower phase noise is obtained at each of the fundamental frequency differential ports. For a similar but fixed frequency oscillator, –2 dBm output power and a low phase noise of less than –90 dBc/Hz is measured at 1 MHz from the 140 GHz carrier.**

I. Introduction

Voltage controlled oscillators (VCO's) with wide tuning range and low phase-noise are essential building blocks for next-generation mm-wave radar and telecommunication systems. The push-push oscillator topology, in which the outputs of two oscillators coupled in anti-phase are combined to yield a strong 2^{nd} harmonic output signal, allows to extent the useful frequency range of available transistor technology and high Q-resonators [1-3].

The advantages of such push-push oscillators in terms of providing high mm-wave output power and low phase noise were successfully demonstrated using different compound semiconductor technologies: 0.13µm GaAs PHEMT oscillators were reported up to 140 GHz [5] and InP HBT oscillators up to 150 GHz [6-8]. Also a number of fixed frequency SiGe -based push-push oscillators, with excellent phase noise and operating up to 58 GHz, were reported in literature[2,4].

SiGe HBT's with cutoff (f_T) and maximum oscillation (f_{MAX}) frequencies well beyond 100 GHz were recently demonstrated in highly manufacturable SiGe BICMOS process technologies [9,10]. Such high-performance HBT's enable to extend the Si-based push-push oscillator topology to higher mm-waves. At these frequencies, it is imperative to monolithically integrate all components of the oscillator.

In this paper, we report a compact fully integrated push-push VCO operating in D-band. This VCO has a very wide tuning range, low phase-noise and differential fundamental frequency outputs enabling additional frequency division.

II. Circuit Design

The schematic diagram of the push-push VCO is shown in figure 1. The circuit diagram is similar to that of the InP D-HBT push-push oscillator we reported in [5]. A strong second harmonic push-push output is obtained at the virtual differential ground node at the end of a line resonator (LB) connected to the base of a differential LC-type Colpitts oscillator. This enables to have both the single-ended second harmonic push-push output and a differential output at the fundamental frequency. Having access to the fundamental frequency output simplifies the locking of this push-push oscillator to a reference clock using a PLL with dynamic frequency divider [2]. Dynamic and static frequency dividers up to V-band have recently been reported in advanced SiGe technologies [9].

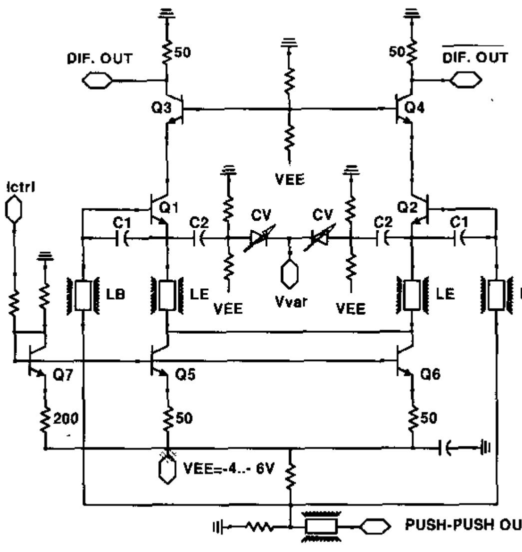

Fig.1: Schematic diagram of the push-push oscillator.

The negative resistance in this Colpitts oscillator is obtained by loading the emitters of Q1 and Q2 with a capacitance formed by the series connection of a fixed MIM capacitor C2 and a p-well junction varactor diode CV. The coplanar transmission lines LE are designed to be quarter wavelength at the fundamental oscillation frequency, such that the differential short at the collector

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of Q5 and Q6 is transformed to an open at the fundamental frequency. In this way, high-impedance and low loss current sources are obtained for the differential mode, while the active current sources formed by Q5 and Q6 loading the lines LE for the common mode prevent the onset of common mode oscillation. While it is still possible to use only active current sources at these frequencies [8], the differential mode loss and non-linearities caused by the base-collector junction of the HBT's in the current mirror will adversely impact both the amount of negative resistance obtainable and the phase noise. A cascode output stage (Q3 and Q4) is chosen both to increase the maximum obtainable frequency of oscillation and to increase the isolation between oscillator and load. The current of the oscillator is set by the current sources Q5 and Q6 through a current mirror Q7. High ohmic resistive frequency dividers are used for biasing the cascode stage, the varactor and the bases of Q1 and Q2. Fixed capacitors C1 bypassing the base-emitter diode limit the non-linear up conversion of noise at the base node.

To reduce the influence of silicon substrate losses and to increase quality factor, conductor backed coplanar waveguide is chosen for the resonator lines LB and quarter wavelength transformer lines LE. The coplanar waveguide conductor is fabricated in the upper 4-µm thick aluminum layer and the bottom copper layer is serving as the thin-film microstrip groundplane. As a good compromise between circuit size, conductor losses, maximum operating frequency and metal layer design rules, a coplanar conductor width of 7 µm was adopted.

We also realized a second oscillator, in which the varactor diodes (CV) were replaced by fixed MIM capacitors. This fixed frequency oscillator oscillates at slightly lower frequency because the value of the smallest size MIM capacitor (67fF) is larger than the capacitance of the two-finger 8x3 µm varactor used in the VCO design.

A chip photograph of the VCO is shown in figure 2. The differential outputs are on the left, the single-ended push-push output on the right. To obtain strong fundamental rejection at the push-push output the very compact layout is made completely mirror symmetric. The total chip size including RF and biasing pads is 650 by 700 μm^2.

II. CIRCUIT RESULTS

Circuits were realized using an advanced 0.13µm SiGe HBT foundry process This process features a high-performance NPN HBT with a transit frequency f_T of 200 GHz, a maximum oscillation frequency f_{MAX} slightly above 200 GHz and a collector-emitter breakdown voltage of 1.8V. To increase output power and reduce overall phase noise, the core VCO circuit was implemented using double finger $8x0.12\mu m^2$ wide emitters.

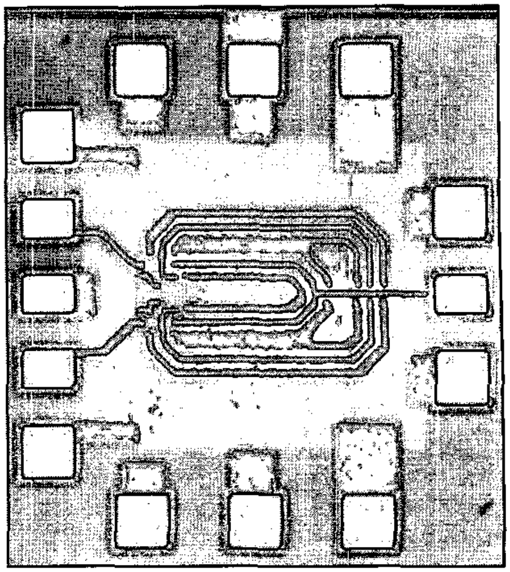

Fig. 2: Chip photograph of the push-push oscillator.

The SiGe VCO output spectrum measured at the single-ended push-push output using an on-wafer GGB Industries WR-05 waveguide probe and a Millitech 140-170 GHz downconverter, is shown in figure 3. This measurement was not corrected for the WR-05 waveguide probe and downconverter loss estimated to be at least 15 dB. A clean spectrum with –10 dBm output power at 154 GHz is obtained for a total power consumption of 170 mW. A maximum of –5 dBm of output power at 150 GHz can be obtained by increasing the current in the VCO. The fundamental component at the push-push output was found to be below the noise floor of the spectrum analyzer.

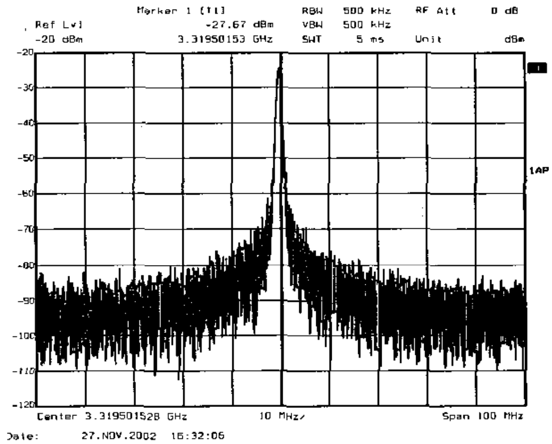

Fig. 3: Downconverted spectrum (LO=151 GHz) of VCO at 2nd harmonic push-push output (VEE: -6.5V, total current: 27mA, not corrected for 15 dB conversion loss, positive image).

Figure 4 shows the output spectrum of the VCO at one of the differential ports. This measurement was performed using a differential GGB Industries 1-mm coaxial probe coupled to a Millitech WR-10 waveguide mixer using a coaxial-to-waveguide adapter. The minimum conversion loss of this setup is estimated between 10 and 12 dB. A maximum output power of more then 0 dBm was obtained at each of the differential probes resulting in a differential voltage swing of more then 1Vpp.

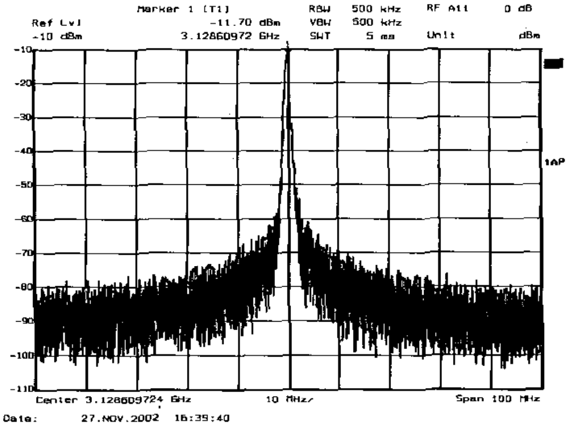

Fig. 4: Downconverted spectrum (LO=74 GHz) of VCO at one of fundamental differential outputs (supply: -6.5V, current: 27mA, not corrected for 10 dB conversion loss, positive image).

The accurate determination of phase-noise performance of VCO's at millimeter wave frequencies is challenging because without a high-isolation output buffer amplifier, the impedance of measurement probe and waveguide components can impact the oscillation frequency. As a result, the relatively high Q of these external components, might artificially improve the measured phase noise [5].

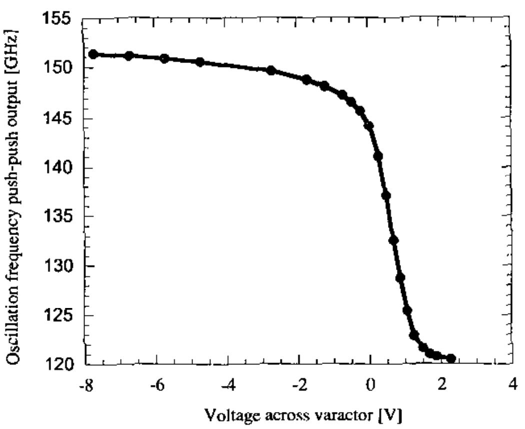

Fig. 5: Measured VCO oscillation frequency versus varactor tuning voltage (supply: -6.5V, total current: 25mA).

As we noticed that for our VCO the load at the differential output is capable of pulling the oscillator frequency, phase noise measurements at the push-push output were performed with the differential pads opened. In the linear tuning range of the VCO, a phase noise of around –85 dBc/Hz was measured at 1 MHz offset from the carrier. The phase noise at the fundamental frequency, measured at identical biasing and loading was measured to be about 6 dB better, so no push-push noise improvement was observed within our measurement accuracy.

As demonstrated in figure 5, a very wide tuning range of 30 GHz (120 to 150 GHz) can be obtained for this VCO topology. The wide tuning range is a result of the series connection of the varactor diode CV with the relatively small capacitor C2. When forward biasing the varactor diode (CV), the emitter of Q1 is loaded by the capacitor C2 in series with the small parasitic resistance of the varactor. In this way, enough negative resistance is generated to sustain a strong oscillation. A drawback of using the varactor in switch-like mode is the reduction in linear tuning range due to the capacitive division ratio between C2 and CV and the increase of phase noise in the non-linear range due to the high tuning sensitivity and poor Q of a forward biased varactor. In this respect, it is better to use MOSFETs as digital tuning devices [10].

The power measured at the push-push and fundamental output as a function of the tuning frequency is plotted in fig 6. A high and flat output power is achieved for the fundamental frequency output suggesting enough loop gain to sustain a strong oscillation. A reduction in the push-push output is noticed below 140 GHz. This reduction in measured output power is mainly caused by the measurement setup, which uses a 140-170 GHz WR-05 waveguide mixer, resulting in excessive conversion losses below 140 GHz.

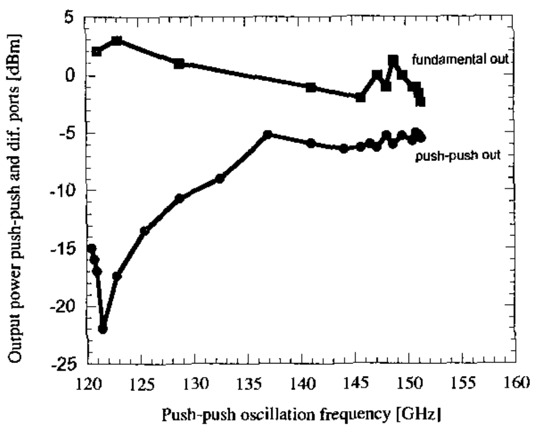

Fig. 6: Measured and corrected power at fundamental and push-push output vs. VCO frequency (VEE: -6.5V, current: 25mA)

The fixed frequency oscillator, in which a capacitor replaces the varactor diode (CV), operates at slightly lower frequency: 140 GHz. Because of the lower loss of the MIM capacitor, both higher output power and lower phase noise are achieved. The output spectrum at the push-push and fundamental output are shown in figure 7 and 8 respectively. Up to –2dBm and +3 dBm of output power are measured at the push-push and fundamental output. The phase-noise measured at the push-push output is less then –90 dBc/Hz at 1 MHz offset from the carrier.

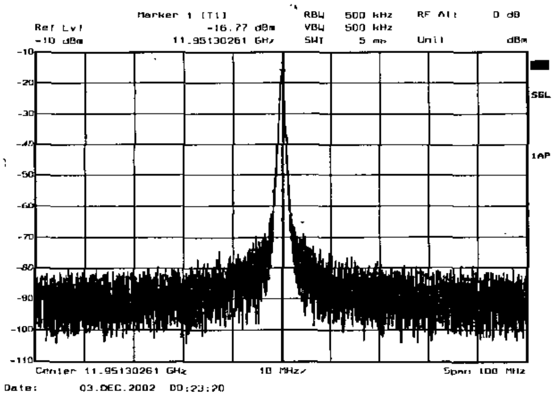

Fig. 7: Downconverted spectrum of fixed oscillator at push-push output (supply: -6.5V, current: 30mA, LO=151 GHz, not corrected for 15 dB conversion loss, negative image).

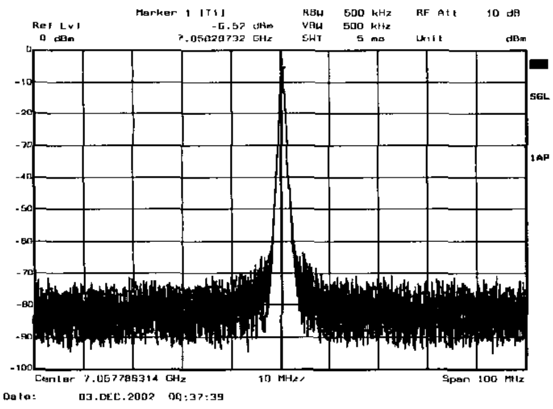

Fig. 8: Downconverted spectrum of oscillator at fundamental output (supply: -6.5V, current: 30mA, LO=62.4 GHz, not corrected for 10 dB conversion loss, positive image).

V. Conclusion

In this paper, we demonstrated a very compact SiGe push-push VCO with up to –5dBm output power at 150 GHz, good phase-noise and a tuning range of 30 GHz. This VCO is, to the best of our knowledge, the highest frequency and widest tunable Si-based VCO.

The obtained results clearly demonstrate the feasibility of realizing high-quality mm-wave sources using low-cost and highly manufacturable Si-based processes. The integration density of these technologies should enable fully integrated PLL-stabilized D-band sources and transceivers. Further improvements in the performance of both SiGe and scaled InP-based HBT's show the promise to realize compact sources generating adequate output power in the submillimeter range (0.2-1 THz).

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