Highly Efficient Harmonically Tuned InP D-HBT Push-Push Oscillators Operating up to 287 GHz

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Abstract — **Integrated push-push oscillators, achieving high output power at 210, 235 and 287 GHz, were realized in a 0.5 µm emitter double-heterojunction InGaAs/InP HBT (D-HBT) technology with a maximum oscillation frequency f_{max} of 335 GHz and a breakdown voltage (V_{bceo}) of 4V.**

The oscillators are based on a balanced Colpitts topology in which a strong second harmonic signal is generated by combining the differential signals at the collector and by reactively tuning the output impedance of the oscillator using a shorted stub. Three oscillators were realized using this topology. A high-power output signal of more then 0 dBm is obtained for oscillators operating at 210 and 232 GHz, an improvement of 5 dB compared to the output power measured on an identical push-push oscillator without 2^{nd} harmonic tuning. Close to -3 dBm output power is obtained at an output frequency of 280 GHz by further reducing the resonator length. By reducing the current, a maximum output frequency of 287 GHz is obtained.

Index Terms — **Bipolar transistor oscillators, Millimeter wave oscillators, heterojunction bipolar transistors (HBTs).**

I. INTRODUCTION

Voltage controlled oscillators (VCO's) with high output power, good DC-to-RF efficiency and low phase-noise are essential building blocks for next-generation millimeter wave and THz telecommunication, and high-resolution radar and imaging systems. The push-push oscillator topology, in which the outputs of two oscillators coupled in anti-phase are combined to yield a strong 2nd harmonic output signal is often used at the highest frequencies [1] as it enables realization of sources even beyond the maximum oscillation frequency (f_{max}) of available active device technologies and allows extension of the frequency range of available resonator technologies. Furthermore, using the push-push topology, a frequency locked source can be realized by locking the oscillator in a phase-locked loop (PLL) using a static or dynamic divider operating at the fundamental frequency instead of at the second harmonic output frequency, reducing divider speed requirements by half .

The potential of push-push oscillators at millimeter wave frequencies has been extensively demonstrated in the past. Push-push oscillators realized in various compound semiconductor technologies were reported in literature: 0.13µm GaAs PHEMT oscillators were reported up to 140 GHz [2], InP HBT oscillators up to 215 GHz [3-6] and SiGe HBT oscillators up to 190 GHz [7,8]. More recently, 132 and 192 GHz push-push oscillators were reported in 90 and 130 nm CMOS technology [9,10]. However, even when using the push-push topology, due to the reduced breakdown voltage of Si-based high-speed technologies, a significant reduction in output power is observed for oscillators reported beyond 100 GHz. For instance, the CMOS oscillators demonstrated -20 dBm output power at 192 GHz [9], which might not be sufficient for many millimeter-wave source applications.

In this paper, we report multiple 0.5 µm InP D-HBT push-push oscillators with high output power up to 287 GHz. We also demonstrate the beneficial effect on the output power of reactively tuning the output impedance for maximum second harmonic generation.

II. SUBMICRON INP D-HBT TECHNOLOGY

InP/InGaAs D-HBT's have demonstrated impressive cutoff frequencies while maintaining a high breakdown voltage with a large band gap collector. We have developed a scaled i-line stepper-defined 0.5 µm InP D-HBT technology [13]. Dry-etched mesas are used to replace the wet etched emitter, base and collector definition to ensure accurate submicron emitter geometry and to enhance the device yield and uniformity. A narrow-base layout is used to reduce the parasitic base-collector capacitance (C_{bc}). The back-end integration of our InP D-HBT MMIC process includes thin-film capacitors and resistors, as well as three levels of gold interconnect with low-k inter-level planarizing dielectric layers.

HBT devices fabricated on the same wafer as the oscillators reported here have maximum extrapolated f_T and f_{max} of 405 and 335 GHz respectively at a current density of 600 kA/cm^2, as shown in figure 1. The measured device breakdown voltage ($V_{BD,CEO}$) is 3.5-4 Volts.

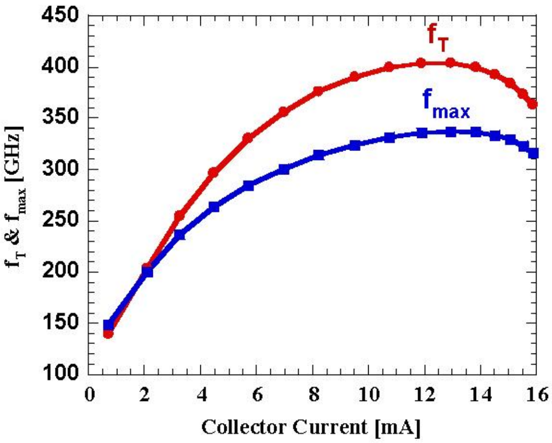

Fig. 1. Extrapolated f_T and f_{max} of 0.5 by 4.0 µm^2 emitter InP D-HBT measured as function of collector current.

III. PUSH-PUSH OSCILLATOR CIRCUIT DESIGN

The schematic diagram of the push-push oscillator topology investigated in this paper is shown in Fig.1. The core of the oscillator is similar to the fixed frequency Colpitts oscillator we reported in [6], with two resonators at both base and emitter (L_B and L_E) for maximum performance [13] and with a capacitor C_B between base and emitter to optimize phase-noise. For this configuration, the second harmonic push-push output can be obtained at the virtual differential ground node, which in fact is only ground for odd harmonics. In general, this second harmonic push-push output can be taken at either the base, emitter or collector terminals of the HBT's. As we reported in [6], the largest signal swing is obtained at the collector by directly shorting the differential output, similar to the drain-connected HEMT push-push oscillators proposed by S. Kudszus [2]. Another advantage of directly shorting the fundamental output at collector is that the large-signal swing at this node is reduced, enabling more robust operation in terms of base-collector breakdown.

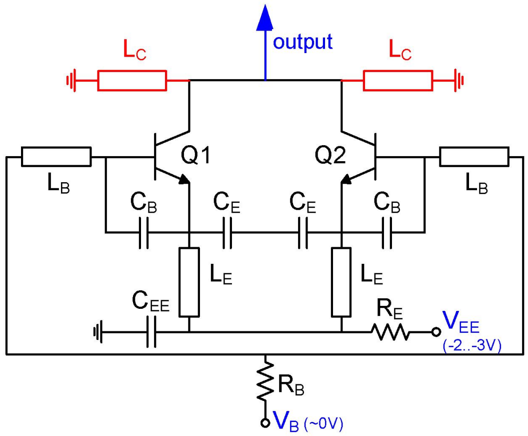

Fig. 2. Schematic diagram of the push-push oscillator.

The fundamental frequency of the push-push oscillator is mainly set by the resonators L_B and L_E and the capacitors C_E and C_B and is (in the first order) independent of the output load. However for the even-order harmonics, the short at the collector becomes an open circuit and therefore the second harmonic output power becomes strongly dependent on the output load seen at the collector. By inductively tuning the output impedance using a shorted stub at the collector (L_C) a 6 dB increase of the power at the second harmonic at 215 GHz is simulated. As an additional benefit, the collector current can now be provided directly through the tuning stubs.

Three tuned push-push oscillators (VCO-1, 2, and 3) were fabricated with different resonator lengths L_B and L_E and simulated oscillation frequencies of respectively 215, 240 and 290 GHz. To verify the effect of the harmonic tuning, a version without stubs was also fabricated. For this version, the collector current was provided through a shorted bias-tee on the waveguide probe sued for on-wafer measurements.

A layout view and a chip photograph of the highest frequency oscillator (VCO-3) are shown in figure 3. The transmission line resonators were implemented in thin-film microstrip (TFMS) using a 2 µm thick plated Au ground plane on top of 7 µm low-k inter-level dielectric ($_r$=2.6). All HBT's (Q_1-Q_2) have 0.5 by 4.0 µm^2 emitter dimension. RC bypass networks were used at different power supplies. The total chip size is 0.35 by 0.45 mm^2.

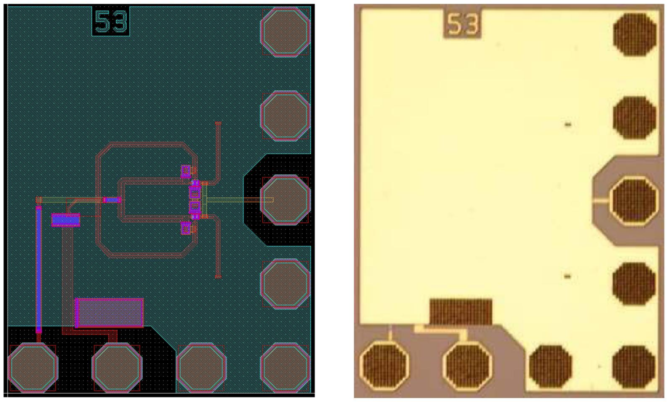

Fig. 3. Layout view and microphotograph of the thin-film microstrip push-push oscillator. The RF output is on the right. Biasing is done through on-chip bias networks. Overall chip size is 0.35 by 0.45mm^2.

IV. MEASUREMENT RESULTS

On-wafer measurements beyond 200 GHz are challenging. In our setup, the output signal of the different oscillators is probed using a GGB Model-325 WR03 waveguide probe and is down-converted using a Virginia Diodes Inc. (VDI) WR03 sub-harmonic mixer driven by a broadband VDI WR06 source. The conversion loss of the mixer alone varies between 7 dB and 12 dB. Including probe and waveguide transition losses and cabling, an overall loss between 11 and 16 dB is expected.

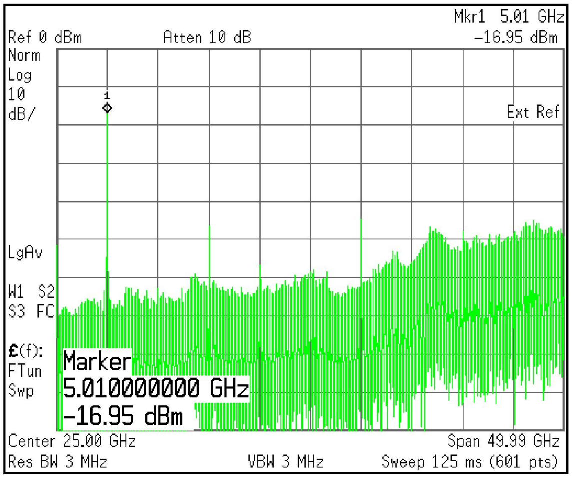

Fig. 4: Downconverted spectrum (LO=280 GHz, USB) of VCO-3 operating at 285 GHz (V_{EE}: -2.1V, total current: 17mA, not corrected for ~11 dB conversion loss)

The downconverted spectrum of the highest frequency VCO is shown in figure 4 for a supply voltage V_{EE} of -2.1V and a total current of 17 mA, corresponding with an HBT current density of 425 kA/cm^2. The measured IF signal of -17 dbm at 5 GHz corresponds with a -6 dBm RF signal at 285 GHz. As can be seen in the detailed spectrum of figure 5, a relatively clean output spectrum is obtained. Unfortunately, accurate phase-noise measurements using a spectrum analyzer are difficult.

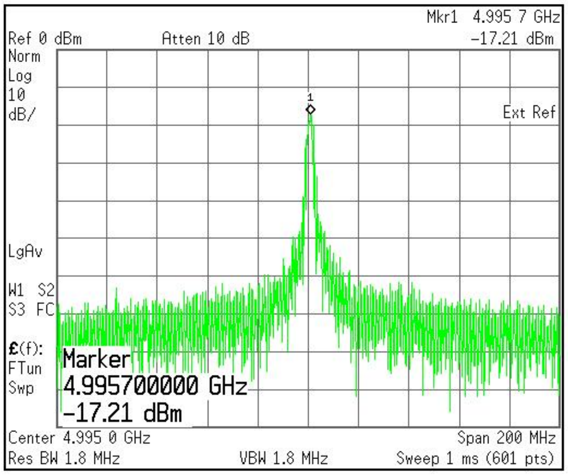

Fig. 5: 200 MHz detail of downconverted spectrum (LO=280 GHz, USB) of VCO-3 at 285 GHz (VEE: -2.1V, total current: 17mA)

As shown in figure 6, the output power can be increased by increasing the overall supply voltage, effectively increasing the total current through the VCO and the base-collector voltage. As shown in figure 6, the oscillation frequency can be tuned between 276 and 287 GHz (4%) by changing the bias supply from -2.9V to -1.2V. The measured output power varies from -17dBm to a maximum of -3 dBm, which is actually higher then the estimated 1-dB compression input power of the VDI WR03 mixer used in this setup.

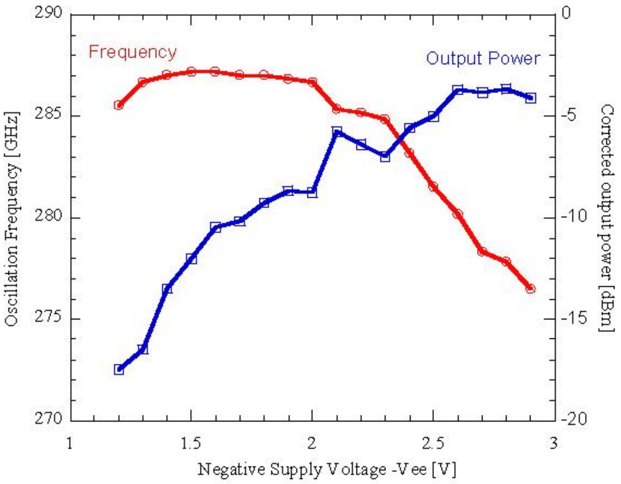

Fig. 6: Measured 2nd Harmonic Frequency and Output Power as function of negative supply Vee (Vb to 0V using external resistor). This measurement was corrected for 11 dB losses.

For all fabricated push-push oscillators a very good agreement was obtained between simulated and measured oscillation frequencies. Table I provides an overview of the measured output frequency, power and efficiency of the 4 oscillators realized in this work and compares the results with previously reported oscillators beyond 100 GHz. Very high overall DC-to RF efficiencies of 2.6, 2.2 and 0.8% are obtained for tuned oscillators operating at respectively 210, 235 and 280 GHz.

For the lowest frequency oscillator, operating at 210 GHz, a 5 dB higher output power is measured for the tuned oscillator compared with the version without stub matching. According to simulations, this improvement would further increase for higher frequencies.

V. CONCLUSIONS

In this paper, we have reported highly efficient and high-power InP D-HBT push-push oscillators operating around 210, 235 and 285 GHz. The output power of these oscillators is shown as a function of oscillation frequency and is compared with all reported oscillators fabricated in various semiconductor technologies in figure 7. As can be seen, thanks to the 2nd harmonic tuning technique and the high breakdown voltage of the 0.5 µm InP D-HBT, our oscillators achieve higher output power and efficiency then the 50 nm InP HEMT fundamental oscillators reported in [12], the only other sources reported so far in this frequency range.

Our simulations indicate that by further reducing resonator length and capacitor size, we should be able to extend this performance up to at least 400 GHz. As such, InP D-HBT based harmonic oscillators will be a prime candidate for delivering high-efficient and high-power sources in the sub-millimeter-wave range.

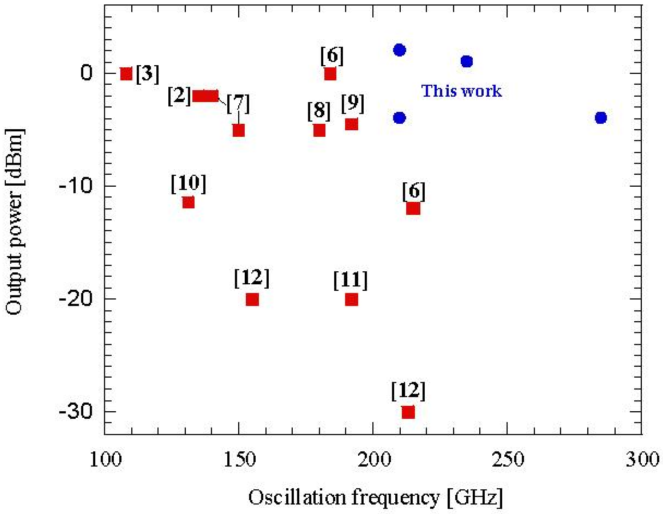

Fig. 7. Overview of reported output power and frequency of operation for oscillator implemented in various technologies.

TABLE II

COMPARISON OF OSCILLATORS OPERATING OVER 100 GHZ REPORTED IN LITERATURE

Ref	Technology	Dimension [µm]	f_T [GHz]	fmax [GHz]	Frequency [GHz]	Output Power [dBm]	DC Power [mW]	DC-to-RF Efficiency [%]	Topology
[2]	GaAs HEMT	0.13	90	160	135	-2	-	-	push-push at drain
[3]	InP HBT	1.0	75	200	108	0	204	0.5	push-push at base
[6]	InP D-HBT	0.5	320	280	184	0	60	1.6	push-push at collector
					215	-12	60	0.1	push-push at base
[7]	SiGe HBT	0.13	200	>200	150	-5	175	0.18	push-push at base, tunable
					140	-2	195	0.32	push-push at base, fixed
[8]	SiGe HBT	0.14	200	275	180	-5	120	0.26	push-push at emitter
[9]	SiGe HBT	0.14	200	275	192	-4.5	215	0.16	push-push at emitter
[10]	CMOS	0.09	142	160	131	-11.4	27.6	0.26	cross-coupled push-push
[11]	CMOS	0.13	-	-	192	-20	16.5	0.06	cross-coupled push-push
[12]	InP p-HEMT	0.05	340	>400	155	-20	7.7	0.13	fundamental oscillator with
					213	-30	7.1	0.014	integrated slot antenna
This work	InP D-HBT	0.5	405	335	210	>2	60	2.6	push-push at collector-tuned
					235	>1	55	2.2	tuned
					285	>-4	45	0.8	tuned
					210	-3	60	0.6	no tuning

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