>300GHz Fixed-Frequency and Voltage-Controlled Fundamental Oscillators in an InP DHBT Process

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Abstract — **We report fundamental fixed-frequency and voltage-controlled oscillators operating at >300GHz fabricated in a 256nm InP DHBT technology. Oscillator designs are based on a differential series-tuned topology followed by a common-base buffer. Measured oscillation frequencies of fixed-frequency designs are 267.4, 286.8, 310.2, and 346.2GHz, at P_{DC}=35mW. At optimum bias, the output power was measured to be -5.1, -6.9, -9.2, and -11.0 dBm for each design (no probe loss correction), with $P_{DC}\leq$115mW. Measured phase noise was -96.6dBc/Hz at 10MHz offset. Varactor-tuned designs demonstrated 10.6-12.3 GHz of tuning bandwidth.**

Index Terms — **Millimeter-wave oscillators, voltage-controlled oscillators, MMIC oscillators.**

I. INTRODUCTION

Sub-millimeter wave (sub-mm-wave) and terahertz (THz) frequencies beyond 300 GHz up to 3 THz have applications in security/medical imaging systems, radar, chemical/bio sensors, and high-rate data communications, taking advantages of short wavelengths and wide available bandwidths. A key element in such sub-mm-wave systems is a compact, tunable signal source with sufficient output power level as a local oscillator (LO).

Oscillator circuits can be specially designed for increased signal power at harmonics enabling RF power generation at close to or beyond the transistor's power gain cutoff freqeuncy (f_{max}) [1][2][3][4]. When the device f_{max} is sufficiently high, fundamental oscillators are generally preferred, since they are simpler and more power-efficient than harmonic-based oscillators, with no need of eliminating sub-harmonic outputs. The highest transistor bandwidths have been reported in indium phosphide-based (InP) high electron mobility transistors (HEMTs) and heterojunction bipolar transistors (HBTs), making these technologies the best candidates for THz integrated circuits.

Fundamental oscillators up to 346 GHz have been demonstrated in an InP HEMT technology [6], producing 0.27mW at 330.56GHz [7], and a fundamental InP HBT oscillator has been reported operating at 311GHz [5]. These previously reported fundamental oscillators were single transistor circuits where the transistor was reactively tuned to be unstable. In this paper, we report on a series of differential oscillator designs with an integrated output buffer and bias circuitry operating up to 346.2GHz. We report results from fixed frequency oscillator designs and for the first time demonstrate voltage controlled fundamental oscillators operating at >300GHz.

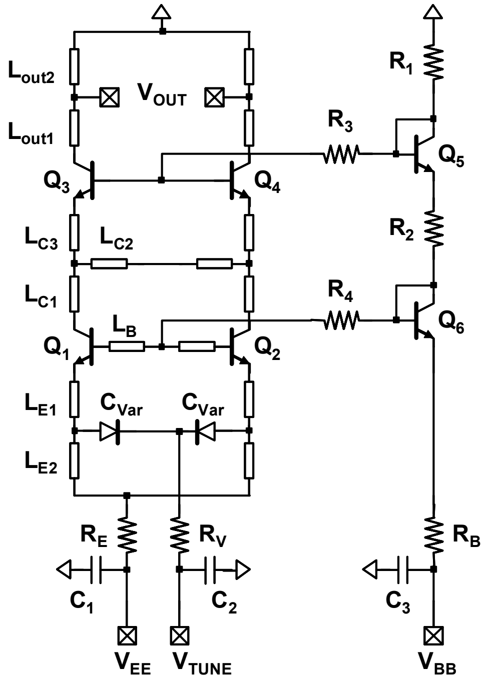

Fig. 1. Simplified schematic of voltage-controlled oscillators (VCO). All HBTs are 3×0.25μm^2 with a single finger. Actual RF output is single-ended, with one V_{OUT} node internally terminated to 50-ohm. Fixed-frequency oscillators share the same topology, but with no varactors.

II. INP HBT TECHNOLOGY

InP double hetorojunction bipolar transistors (DHBTs) offer high transistor bandwidth with high voltage handling due to the use of a wide bandgap InP collector. In this work, circuits

TABLE I
SUMMARY OF FIXED-FREQUENCY OSCILLATOR RESULTS

Oscillation frequency			Single-ended output power[1] (dBm)		
Design	Measured	Simulation w/ revised HBT model	Simulation w/ revised HBT model[2]	Meas.(uncorrected)	Meas. (corrected[3])
292.4 GHz	267.4 GHz	261.5 GHz	-3.6 dBm	-5.1 dBm	-2.1 dBm
315.4 GHz	286.8 GHz	280.6 GHz	-4.7 dBm	-6.9 dBm	-3.9 dBm
336.5 GHz	310.2 GHz	303.7 GHz	-6.4 dBm	-9.2 dBm	-6.2 dBm
387.8 GHz	346.2 GHz	346.0 GHz	-7.7 dBm	-11.0 dBm	- [4]

[1] V_{EE} and V_{BB} tuned for maximum measured power. P_{DC}=110mW, 78mW, and 76mW, and 115mW, for oscillators from top to bottom.

[2] 1 dB of inverted-microstrip-to-GSG-pad loss included

[3] Accounting for 3dB of RF probe loss from manufacturer's data

[4] Probe loss data unavailable above 325 GHz

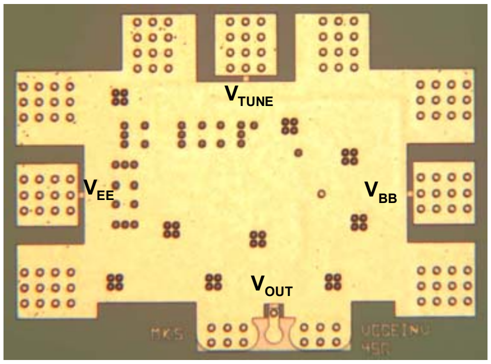

Fig. 2. VCO chip photograph (740µm×550µm). The entire circuit except pad areas is covered by a M3 ground plane.

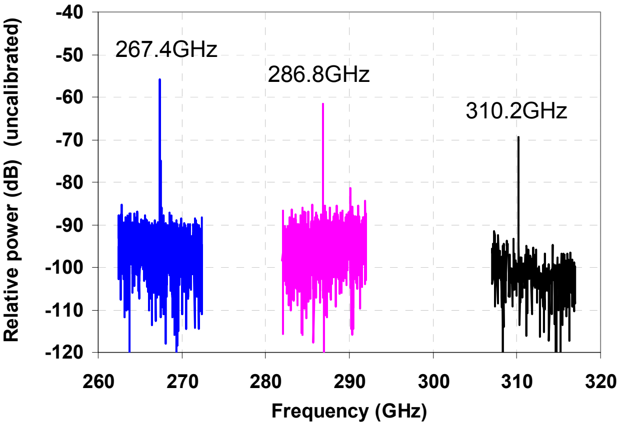

Fig. 3. Measured spectra of three fixed-frequency oscillators at the output of a WR-3 OML VNA extender (346.2 GHz design is not shown). Power levels are uncalibrated (HP8510C IF unit was used for this measurement). Oscillators are biased at V_{EE}= -3.8V (6.4mA) and V_{BB}= -3.8V (2.8mA), with 35mW of total dc power consumption.

were fabricated on 4-inch semi-insulating InP substrates with device layers grown by molecular beam epitaxy. The epitaxy utilizes a 30nm carbon-doped base layer and a 150nm N-InP collector region. The emitter contact is patterned using electron-beam lithography and formed using an Au-based electroplating process [8]. In this work, the nominal emitter junction width was 0.25µm. A thin (<100nm) emitter semiconductor stack minimizes undercut during the self-aligned emitter mesa etch. Dielectric sidewall spacers are formed that passivate the base-emitter junction and permit the formation of a self-aligned base contact. After base-contact deposition, the remaining HBT process flow follows that of a standard mesa-HBT process. The transistors are passivated with a spin-on-dielectric (Benzocyclobutene, BCB), and a planarization etch is used to expose the emitter post. Device vias are opened to the remaining HBT contacts and first-level interconnects are formed using electroplated gold.

The HBT IC process includes thin-film resistors (50 Ohm/sq), MIM capacitors, and 3-levels of interconnect (M1-M3). A 10µm thick BCB layer is used between M2 and M3 to facilitate the formation of low-loss thin-film microstrip lines.

Transistor characterization was performed on the fabricated wafers. S-parameter measurements of transistors were performed from 1-110GHz and RF figures-of-merit were extracted from these measurements. A 4×0.25µm^2 HBT demonstrated an extrapolated current gain cutoff frequency (f_τ) of 375GHz and an extrapolated maximum frequency of oscillation (f_{max}) of >650GHz, at I_C= 9mA and V_{CE}= 1.8V. Transistors have demonstrated common-emitter breakdown voltages (BV_{CEO}) of >4V.

II. CIRCUIT DESIGN

Figure 1 illustrates the circuit schematic of the oscillator designs. A series-tuned oscillator topology (T-network feedback) was chosen because it is less affected by layout parasitics and transmission line discontinuities than a traditional Colpitts configuration (π-network feedback), a critical advantage at sub-mm-wave frequencies. The differential oscillator configuration offers significant advantages over single-ended designs. The differential operation creates a virtual ground along the plane of symmetry, making the oscillator operation insensitive to

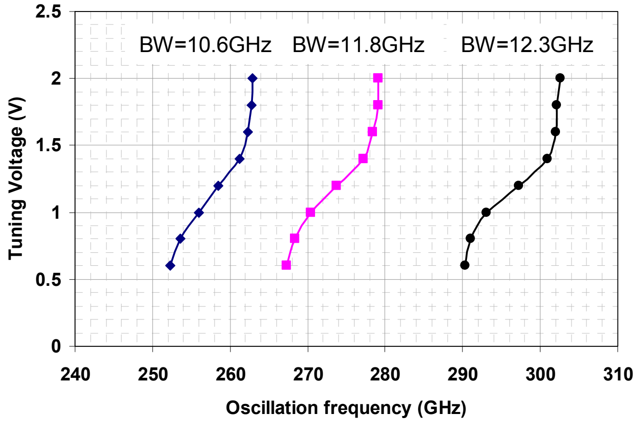

Fig. 4. Measured tuning bandwidth of three VCOs. Tuning voltages are referenced to V_{EE} (= -3.8V). Same bias applies as in Fig. 3.

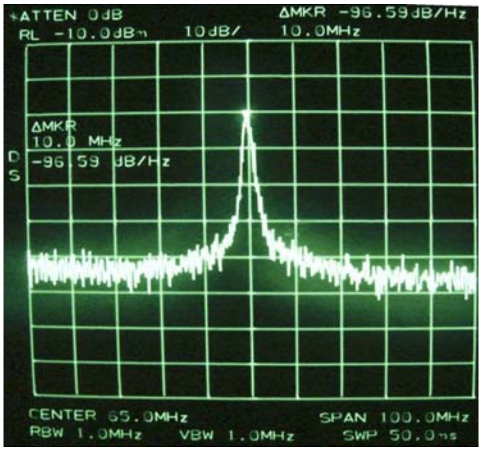

Fig. 5. Measured phase noise of the 286.8GHz fixed-frequency oscillator at the IF output of a WR-3 OML VNA extender using HP8565E: -96.6 dBc/Hz @10MHz offset.

common-mode impedance such as the base/emitter bias circuitry, varactor bias lines, and collector grounding vias (which are ~10μm long). Additionally, differential oscillator outputs enable fully differential transceiver architectures, thus improving common-mode noise rejection and LO leakage cancellation. Finally, the differential output power is 3dB higher compared to single-ended designs under the same HBT bias. All these benefits are obtained at the expense of increased dc power consumption and chip area. In addition, care must be taken to eliminate the possibility of common-mode oscillations.

In the circuit schematic in Fig. 1, Q_1-Q_2 form a differential oscillator core. Q_3-Q_4 are configured as a common-base (CB) amplifier, providing power gain and reverse isolation from load perturbation, while re-using the same bias current as Q_1-Q_2. The oscillation frequency is determined by the impedance seen from the Q_1-Q_2 base, emitter, and collector nodes. Tuning bandwidth can be controlled by balancing L_{E1} and L_{E2}, for a given C_{VAR} and emitter impedance; longer L_{E2} will increase the tuning range, but the oscillation power can suffer if C_{VAR} does not have a sufficiently high quality-factor. The amount of core power coupling to the CB buffer can be adjusted by "step-down" inductance L_{C2}. The additional series line L_{C3} increases flexibility in layout, since Q_3 and Q_4 must be as close to each other as possible. L_{out1} and L_{out2} provide impedance match to 50ohm load at the CB buffer output. Base voltages of Q_1-Q_4 are defined by diode-connected HBTs (Q_5-Q_6) and R_1-R_2. Series bias resistances R_3-R_4 improve common-mode stability. All HBTs are 3×0.25μm^2 with a single finger, nominally biased at the emitter current density of J_E=4.3mA/μm^2 with V_{EE}=V_{BB}= -3.8V. C_{VAR} is a two-finger base-collector (*B-C*) junction at reverse bias, carefully sized for optimum quality-factor (expected Q~15 at 320GHz). Load pull simulations suggest that oscillation frequencies typically change by ±1 GHz at -15dB of load impedance mismatches. In-house physical HBT model was used for the oscillator design, where device parasitics were modeled as a function of device geometry.

All transmission lines in Fig. 1 are inverted-microstrip lines, where M2 and M3 constitute the signal line and ground plane, respectively. A large continuous ground plane is thus guaranteed, with M1 and M2 available for low-inductance local interconnects (M1 and M2 are separated by 1μm of BCB dielectric). Except for the output 50-ohm lines (W=16μm), relatively narrow lines (W=5μm) are used for higher line aspect ratio. This approach minimizes the effects of line discontinuities (e.g. bends, *T*-junctions, crosses, etc) at the cost of slightly higher line loss (~2dB/mm at 320GHz). A VCO chip photo is shown in Fig.2.

III. MEASUREMENT RESULTS

The output of the oscillators was measured on-wafer using a WR-3 GGB Industries wafer probe. To measure the frequency spectrum, the output signal was down-converted by a WR-3 OML VNA extender. The extender's IF output was received by HP8510C configured for an unratioed reflected power (b_1) measurement. This setup enables wideband spectrum scan by sweeping the VNA LO frequency (f_{LO}). Figure 3 summarizes the measured spectra of three fixed-frequency oscillators with 10GHz individual spans. Total dc power consumption was 35mW, with V_{EE}=V_{BB}= -3.8V (J_E=4.3mA/μm^2 for all HBTs). Similar measurements were performed to measure output frequencies from the VCO designs. These results are shown in Fig. 4. Tuning voltages were varied from V_{TUNE}= V_{EE}+0.6V to V_{EE}+2V, which corresponds to 0V and 1.4V reverse bias for internal *B-C* varactors. The measured tuning bandwidths were 10.6GHz, 11.8GHz, and 12.3 GHz, for three VCOs centered around 260GHz, 275GHz, and 300GHz, respectively.

HBT devices, due to their lower 1/*f* noise compared with HEMTs, have the potential for low phase-noise oscillators.

Measured phase noise of the 286.8GHz fixed-frequency oscillator was -96.6dBc/Hz at 10MHz offset from the carrier (Fig. 5). This measurement was carried out by providing a constant f_{LO} and observing the VNA extender's IF output on a spectrum analyzer. By monitoring the IF frequency shift resulting from a change in f_{LO}, the LO harmonic number can be identified, which in turn confirms the RF oscillation frequency.

A total of 22 fixed-frequency oscillators (286 GHz design) were measured across a full 4-inch wafer. The measured spread in oscillation frequency was ±1 GHz for 77% of the measured samples. The maximum deviation in oscillation frequency was 6GHz.

The output power of fixed-frequency oscillators was measured on-wafer using a WR-3 wafer probe that was attached to an Erickson Instruments calorimeter through a WR3-to-WR10 taper. Maximum output power was obtained at J_E=7-10mA/μm^2, with the total dc power from 76mW to 115mW. Under the optimum bias, the measured output power was 312μW (-5.1dBm), 205μW (-6.9dBm), 120μW (-9.2dBm), and 80μW (-11.0dBm), for 267.4GHz, 286.8GHz, 310.2GHz, and 346.2GHz design, respectively. RF probe loss was not de-embedded, which is ~3dB according to the manufacturer's data. Fixed-frequency oscillator results are summarized in Table I. The measured oscillation frequencies were lower than design by 9-10%. Initial HBT models used in the design cycle were based on projected transistor performance determined from the transistor geometry and epitaxy design. The HBT model was revised to match measured transistor data, and simulations now predict the oscillation frequencies to within 3% of measurement (Table I). Figure 6 presents performance comparison of recently reported mm-wave oscillators.

III. CONCLUSION

Oscillators operating at >300GHz have been demonstrated in an InP DHBT technology, designed toward integrated THz radio systems. To the best of authors' knowledge, the oscillators presented in this paper are among the highest frequency fundamental oscillators using three-terminal devices. The measured output power was comparable to HEMT oscillators. Varactor-tuned designs exhibit >10GHz of tuning bandwidth, the widest among reported beyond 300GHz.

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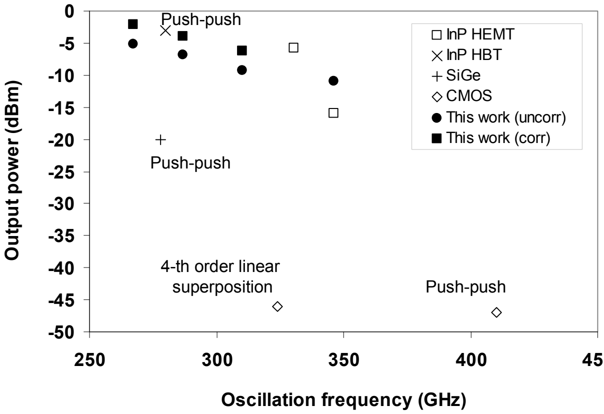

Fig. 6. Recently reported mm-wave oscillators beyond 250GHz.

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