A GaN Differential Oscillator With Improved Harmonic Performance

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***Abstract*—The first AlGaN/GaN HEMT based differential oscillator is reported. The MMIC oscillates at a frequency of 4.16 GHz and provides 22.9 dBm of power from one side at a biasing of V_{gs} -1 V and V_{ds} 20 V. The HEMTs each have a 0.7 μm × 200 μm gate. The second harmonic is 45 dB below the carrier and the third harmonic is more than 70 dB below the carrier. To our knowledge, this is the best reported harmonic performance for a GaN oscillator. The oscillator efficiency is between 4% and 9.4% depending on bias. The measured phase noise is -86.3 dBc and -115.7 dBc at offsets of 100 kHz and 1 MHz respectively. The phase noise at a 1 MHz offset is similar to the noise performance of FET based differential oscillators in other technologies.**

***Index Terms*—AlGaN, cross-coupled, differential, GaN, harmonics, high electron-mobility transistor (HEMT), oscillator.**

I. INTRODUCTION

AlGaN/GaN high electron-mobility transistors (HEMTs) are recognized as the high-power, high-frequency device of choice for future wireless, space, radar, and test applications. GaN-related materials have many times the breakdown voltage and power density of other technologies, such as gallium arsenide, indium phosphide, and silicon. Excellent power performance has been reported for devices [1], as well as for MMIC amplifiers [2]. A larger voltage across the tank of an oscillator gives better phase noise performance [3], which makes GaN an attractive alternative for low-noise integrated analog electronics. Other AlGaN/GaN circuits are starting to appear in the literature, but there are only a few published results. For GaN oscillators, half of these papers are for hybrid systems [4], [5]. For MMIC GaN oscillators, only three have been reported in the literature [6]–[8]. While the previous results have shown good power and phase noise performance, no harmonic performance comparisons have been published. Also, no differential oscillators have been reported. Differential oscillators are convenient to connect directly to a differential input, such as a balanced mixer in an integrated circuit system. If the output of a differential oscillator is taken differentially then the even order harmonics will cancel, giving better harmonic performance. Because GaN oscillators can generate large output signals, it is easier to design for linearity. GaN oscillators also have the advantage of not needing an amplifier gain stage between them and a load, simplifying the circuit. Because high-frequency GaN HEMTs can have breakdown voltages above 100 V, no protection circuitry is needed. A GaN-based system will be less complex, and thus smaller. A GaN MMIC differential oscillator with very low harmonic distortion is presented.

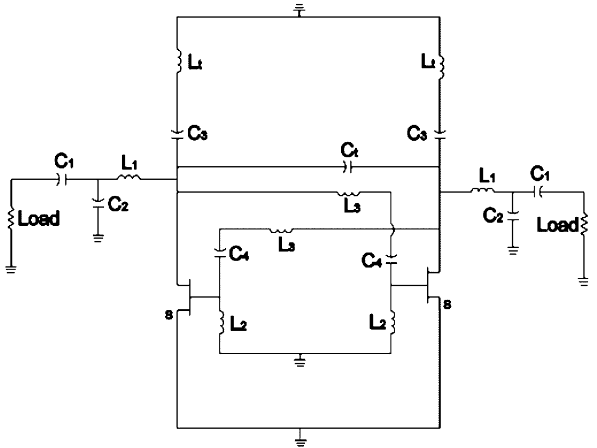

Fig. 1. Circuit schematic of the oscillator. Biasing not shown.

II. CIRCUIT DESIGN AND SIMULATION

The differential oscillator was designed for power and harmonic performance while trying to keep good phase noise performance. A design with a fixed *LC* tank and without a tail current source was chosen to help with phase noise performance. A circuit schematic of the oscillator is shown in Fig. 1. Inductance values were picked for best Q performance. An LC L-match was used to match the oscillator outputs to 50-Ω loads. Using components with high Q values for these narrow band matches will also help the harmonic performance. The circuit was simulated using Agilent Advanced Design System (ADS). The HEMTs were fitted using a bias-dependent, scalable EE_HEMT1 model that includes both small-signal and large-signal modeling. This modeling was performed in the frequency range from 50 MHz to 25 GHz. Passive components were designed based on measurements of fabricated capacitors and inductors at 5 GHz. Typical unloaded Q values at 5 GHz are 25 and 65 for the square spiral inductors and the SiN capacitors respectively. Transient and harmonic simulations were performed. Monitoring these, along with the dynamic load-line at the drain port of the HEMTs, the circuit was optimized to give as linear an output as possible.

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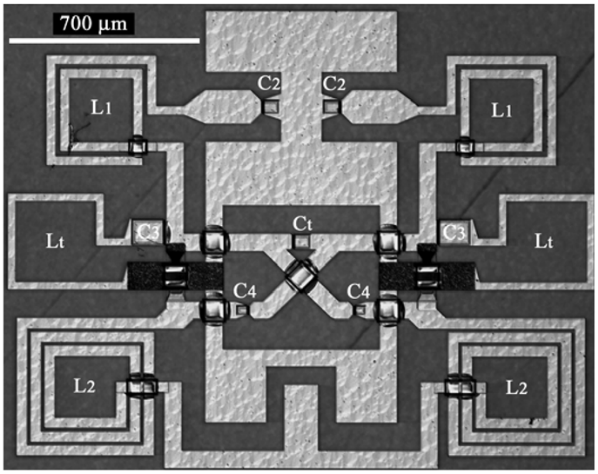

Fig. 2. Photograph of the oscillator.

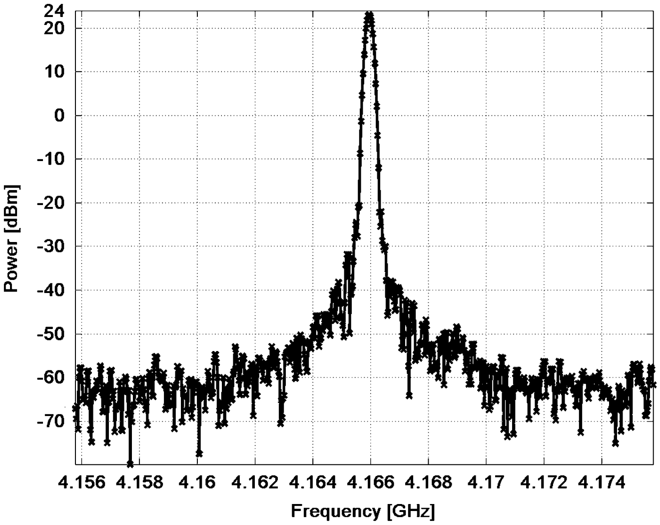

Fig. 3. Measured single-side oscillator power of 22.9 dBm from a spectrum analyzer. The spectrum analyzer span is 10 MHz and resolution bandwidth is 33 kHz. Circuit biasing is $V_{gs} - 1$ V and Vds 20 V.

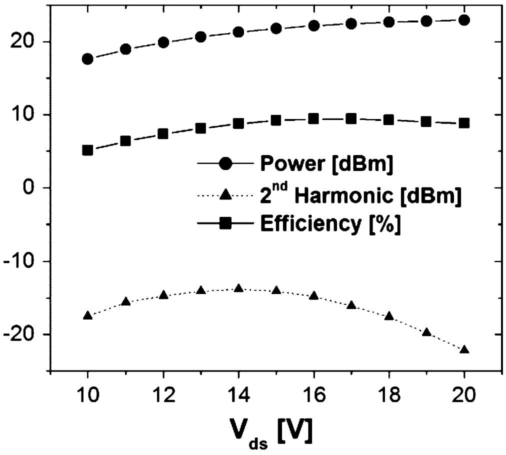

Fig. 4. Power at the fundamental and second harmonic (one side) and efficiency (full circuit) against drain-source bias for the oscillator. Gate voltage is -1 V.

III. CIRCUIT FABRICATION

The material was grown by metal organic chemical vapor deposition (MOCVD) on a c-plane SiC substrate. The epitaxial structure consists of an AlN nucleation layer, a semi-insulating Fe-doped GaN base layer, an unintentionally-doped GaN layer, and finished with an $Al_{0.27}Ga_{0.73}N$, silicon-doped, barrier layer. The room temperature sheet electron concentration and Hall mobility are 1×10^{13} cm^{-2} and 1450 cm^2/Vs, respectively. The GaN HEMTs each have a gate length and width of 0.7 μm by 200 μm, having 100 μm fingers. The unity current gain cutoff frequency (f_t) of the devices is 20 GHz.

Fabrication began with our standard HEMT process [9]. Capacitors were made with the SiN used for device passivation as the dielectric and the metal used for the gates as the bottom electrode. Spiral inductors were made using a metal-dielectric-metal process to provide the bridge needed for the crossovers. The top connection to the capacitors are finished with this process as well. The circuit, shown in Fig. 2, is of size 2 mm × 1.65 mm. The circuit size could have been made smaller by not using large RF chokes—inductances L_2 in Fig. 2—at the expense of performance.

IV. MEASUREMENT RESULTS

Measurements were performed on-wafer using air-coplanar probes and off-chip bias-Ts for the drains and gates. One side of the oscillator was terminated in a 50-Ω load. The power was measured using an Agilent E4440 spectrum analyzer. In Fig. 3, the maximum power for one side of the oscillator is plotted; the center frequency is 4.166 GHz. The data was taken with the analyzer set to a 10-MHz span and a resolution bandwidth of 33 kHz. The circuit is biased at V_{ds} 20 V, I_{ds} 233 mA, and $V_{gs} - 1$ V. The peak power is 22.9 dBm and the efficiency is 8.8%. In Fig. 4, the power, second harmonic, and efficiency are plotted against the drain-source bias. The third harmonic did not appear, and is therefore more than 70 dB below the carrier. The power at the fundamental increases from 17.6 dBm to 22.9 dBm as V_{ds} increases from 10 V to 20 V while the second harmonic ranges from 34.5 dBc to 45.1 dBc from the carrier. To our knowledge this is the best reported harmonic performance for a GaN oscillator. The efficiency has a minimum of 5.1% and maximum of 9.4% for this measured range. It can be seen that power efficiency is sacrificed to produce a more linear output.

The phase noise was measured using an HP3048 phase noise system from a 500 Hz to a 1 MHz offset from the carrier using a PLL technique. A plot of the phase noise data is displayed in Fig. 5, with the circuit biased the same as in Fig. 3. A $1/f^3$ line is included for reference. Phase noise is -86.3 dBc/Hz and -115.7 dBc/Hz at offsets of 100 kHz and 1 MHz, respectively, showing a very good agreement with a $1/f^3$ slope at these points and the other offsets. These values agree with measurements of phase noise performed with a spectrum analyzer.

A comparison of MMIC, FET-based, oscillators is in Table I. Compared in the table is the total power at the fundamental, second harmonic, and third harmonic, the best efficiency, and the phase noise at 100-kHz and 1-MHz offsets. The carrier frequency and gate width, if they were specified, are also listed. The first three oscillators in the table are GaN oscillators, the last two oscillators are differential oscillators in other materials,

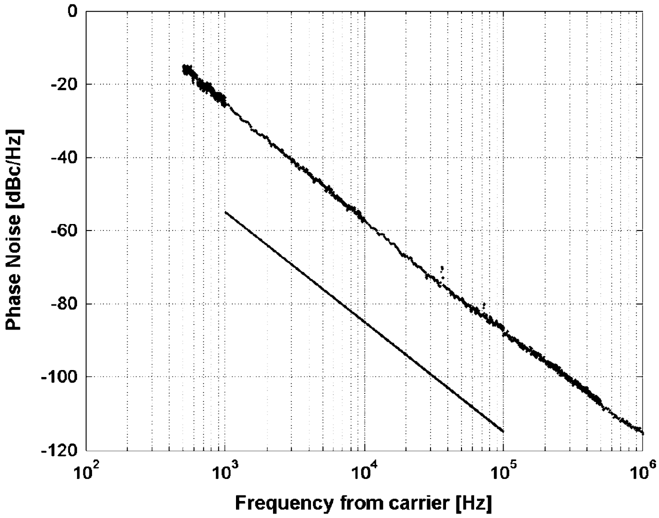

Fig. 5. Phase noise performance at a bias of $V_{gs}-1$ V and V_{ds} 20 V.

TABLE I
COMPARISON OF THE OSCILLATOR WITH MMIC, FET-BASED, OSCILLATORS IN GaN AND DIFFERENTIAL OSCILLATORS IN OTHER TECHNOLOGIES [10], [11]

	Car. Freq.	**Gate Width**	**Fund. Pow.**	**2^{nd} Har.**	**3^{rd} Har.**	**Best Eff.**	**Phase Noise 100kHz**	**Phase Noise 1MHz**
	GHz	mm	dBm	dBm	dBm	%	dBc/Hz	dBc/Hz
GaN HEMT Colpitt's [7]	5.0	0.2	20.5	-11.5	--	14.1	-105	-123
GaN HEMT Hartley [6]	9.56	1.5	32.3	--	--	16	-87	-115
GaN HEMT VCO [8]	9±0.5	1.5	31.8	10.8	4.8	21	-77	--
This Work	**4.16**	**0.4**	**25.9**	**-19.2**	**< -55**	**9.4**	**-86.3**	**-115.7**
GaAs MESFET Diff. [10]	6.44	--	4.67	--	--	--	-93	-112
Si FET Diff. [11]	4.7	0.286	-9	--	--	~2	-90	-110

using similar circuit topologies, and the oscillator fourth down in the table is this work. The power of our oscillator is an order of magnitude more powerful than similar circuits in other technologies. This is true even when device size is taken into account. The phase noise at 1-MHz for the different MMIC differential oscillators is comparable, but at closer-to-carrier offset frequencies the other technologies perform better. This is because their phase noise increases at a $1/f^2$ slope whereas the GaN MMIC oscillators increase at a $1/f^3$ slope. Improvements in material quality, noise modeling, and advanced circuit designs will fix this problem in GaN oscillators. Comparing this work to the other MMIC GaN oscillators, we find similar power and noise performance but superior harmonic performance.

V. CONCLUSION

The first GaN differential oscillator was reported. The output power was found to be comparable to other GaN oscillators while at least 10 times larger than differential oscillators in other technologies of similar topology, size, and biasing. The phase noise performance at large offsets is the same as in other technologies, and similar when compared to other GaN MMICs. The harmonic performance, to our knowledge, is the best reported for a GaN oscillator and appears to be better than similar differential oscillator designs in other technologies.

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