A 110-GHz Push-Push Balanced Colpitts Oscillator Using 0.15-µm GaN HEMT Technology

Jiayou Wang^#1, Yin-Cheng Chang*, Yeke Liu^, Sih-Han Li^$, Da-Chiang Chang*, Yi Huang#, Shawn S. H. Hsu^
^Institute of Electronics Engineering, National Tsing Hua University, Hsinchu, Taiwan
#Department of Electrical Engineering and Electronics, The University of Liverpool, Liverpool, UK
*Taiwan Semiconductor Research Institute, National Applied Research Laboratories, Hsinchu, Taiwan
$Industrial Technology Research Institute, Hsinchu, Taiwan
[1]Jiayou.wang@liverpool.ac.uk

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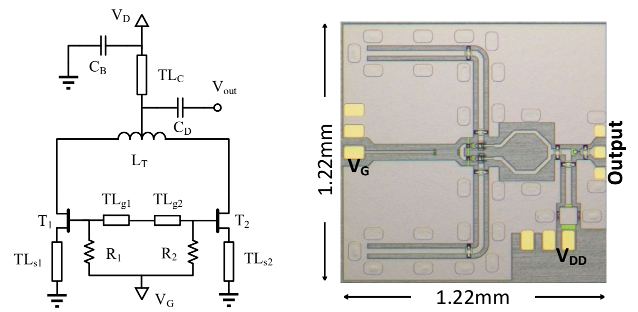
***Abstract*— This paper presents a sub-THz oscillator using 0.15-µm GaN HEMT technology. A push-push balanced Colpitts topology is proposed to achieve a very high operating frequency while also with high output power under low DC power consumption. The source-floating transistor with an in-house built three-terminal transistor model was employed to allow using the transmission line (TL) at the source node for Colpitts feedback capacitor with improved negative resistance. In addition, the layout is in Grounded-CPW (GCPW) configuration with backside vias to achieve an optimized low-loss TL structure. The measured results show that the GaN oscillator can reach a peak output power of -2.1 dBm with a tuning range from 107.9~109.5 GHz, and the measured phase noise is -110.8 dBc/Hz at a 10 MHz offset.**

***Keywords*—GaN HEMT, oscillator, push-push, Coppitts, small-signal model, sub-THz.**

I. Introduction

Wireless communication and radar sensing and imaging using sub-THz/THz technologies have recently been an appealing research topic and industry application. One issue is the so-called "THz gap" because the technology for signal generation with sufficient output power is still very challenging in this frequency range. The conventional approach mainly uses relatively bulky optical devices for THz signal generation [1]. With the advantages of large breakdown voltage and high saturation velocity, the GaN-based devices are promising for such applications. GaN MMIC oscillators operating in the range of RF, mm-wave, and sub-THz have been reported, and good results were obtained. An X-band Class-E power VCO in 0.25 µm GaN/SiC achieved an output power of 27.9 dBm at 9.4 GHz [2]. A single-ended oscillator with a two-stage buffer based on 0.12-µm GaN HEMT operated at a frequency of 74.5 GHz with an output power of 2.2 mW [3]. The oscillation frequency has been constantly pushing up to W-band, with the state-of-the-art 180 GHz using 60-nm GaN HEMT technology [4]-[5].

This paper reports a push-push balanced Colpitts oscillator by 0.15-µm GaN HEMT technology. Using the Colpitts topology with the feedback capacitance realized by the transistor parasitic capacitance, the proposed oscillator can reach a very high operating frequency under a relatively low power consumption. Also, a three-terminal small-signal model is built to enable the design of the source capacitance in the Colpitts topology. Furthermore, the ground-CPW (GCPW)



(a) (b)

Fig. 1. (a) schematic and (b) chip photo of the proposed oscillator.

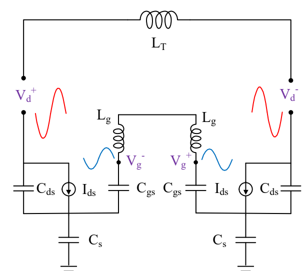


Fig. 2. Small-signal equivalent circuit model of the oscillator (excluding 2nd harmonic output).

structure utilizing the backside metal and through-wafer-vias (TWV) is optimized by full-wave EM simulation to achieve low-loss transmission for sub-THz operation. The proposed oscillator achieves an operating frequency of 109.5 GHz and an output power of -2.1 dBm. To the best of our knowledge, the proposed GaN oscillator reaches the highest oscillation frequency compared with prior reported works using the GaN HEMT technologies with the same gate length.

II. Circuit Topology and Design Considerations

A push-push balanced Colpitts oscillator with the 2nd harmonic output is proposed as shown in Fig. 1(a). Fig. 1(b) shows the MMIC micrograph, fabricated by WIN Semiconductor 0.15-µm GaN HEMT technology.

A. Push-push Balanced Colpitts Topology

The balanced Colpitts topology is employed in this design. As shown in Fig. 1(a), TL_{g1}/TL_{g2} is the transmission line that

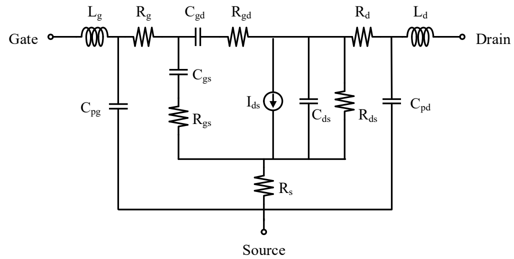


Fig. 3. Small-signal equivalent circuit model of the GaN HEMT.

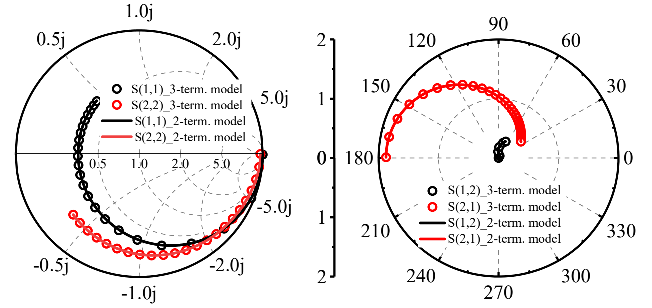


Fig. 4. Comparison of S-parameters between the foundry-provided 2-terminal and the customized 3-terminal model.

connects balanced transistors of which the equivalent inductance is L_g. TL_{s1} and TL_{s2} provide the DC path to the ground as well as the required capacitance C_s at the fundamental frequency (f_0). In addition, L_T is the resonating inductor for the LC tank. The equivalent small-signal model of the resonating core at the fundamental tone is shown in Fig. 2. The drain nodes of the two transistors feature anti-phase oscillation signals at f_0, enabling the in-phase combination of 2nd harmonic ($2f_0$) at the center node of the resonating tank inductor L_T. It should be emphasized that the capacitive feedback path of the Colpitts topology is formed by the parasitic capacitance C_{ds} of the GaN transistor together with the equivalent source capacitance C_s realized by TL_{s1} and TL_{s2}. Note that a properly designed source capacitance can enhance the negative resistance under low power consumption. By using the relatively small parasitic C_{ds} directly for one of the feedback capacitors, this topology can achieve high-frequency and low-power operation simultaneously.

B. Three-terminal GaN Transistor Modeling

Considering the transistor breakdown voltage exceeding 120 V and the maximum current density of ~ 1A/mm, a transistor size of 2×30 µm is selected to meet the desired operating frequency and output power. The transistors are fabricated on the GaN-on-SiC substrate, and the top metal layers can be connected to the backside metal using the TWV in the size of 60 µm × 30 µm. Note that the typical device provided by the foundry is with the source connected to the backside ground through the TWVs, and the corresponding device model only has two terminals. This becomes an issue since the Colpitts topology in the proposed design needs to have the source connected to a capacitor instead of connecting to the ground directly.

The source-floating transistor with backside vias removed is employed to solve this problem, and a customized small-signal transistor model is established and validated for design optimization. Fig. 3 shows the schematic of the small-signal model of the GaN HEMT. The initial value of each passive component in the model is extracted by the pinch-off Cold-FET method. The Levenberg-Marquardt algorithm is used for each parameter iteration for fast convergence [6]. Table 1 lists all the parameters in the model for a 2×30 µm GaN (V_G = -1.5 V and V_D = 25 V). Fig. 4 shows validation of the established 3-terminal model by comparing the S-parameters with the foundry-provided 2-terminal model, and excellent agreement is observed. Based on the established 3-terminal model, the parasitic inductance due to the TWV can be removed, which can be utilized for the design and optimization of the transmission line C_S in the proposed push-push Colpitts oscillator.

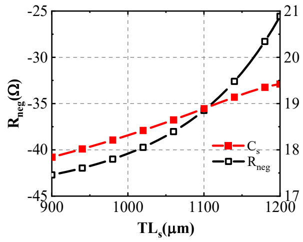
Table 1. Parameters of the Small-signal Model

L_s (pH)	L_d (pH)	L_g (pH)	R_s (Ω)	R_g (Ω)	R_d (Ω)	R_{gs} (Ω)	R_{ds} (Ω)
22.06	23.65	35.13	9.01	7.15	11.73	3.38	4450
R_{gd} (Ω)	C_{pg} (fF)	C_{pd} (fF)	C_{gd} (fF)	C_{gs} (fF)	C_{ds} (fF)	g_m (mS)	
23	13.74	13.35	4.44	114.7	14.39	22.94	

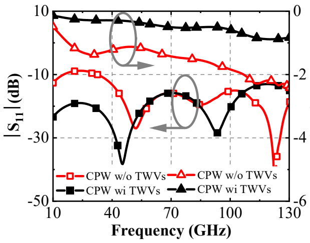
C. Oscillator Design and Optimization

The generation of negative resistance R_{neg} is probably the most important step in oscillator design. Connecting a source capacitor in a FET transistor can increase the unstable region, and enhance the negative resistance. As illustrated in Fig. 1, the transmission lines TL_s are designed for obtaining an equivalent capacitive element at the source of the transistor and also for DC bias. Fig. 5(a) shows the simulated R_{neg} (negative resistance seen from the drain nodes of the balanced core) versus the length of TL_s (exceeding a quarter wavelength at f_0), together with the associated equivalent capacitance of TL_s. The results indicate that R_{neg} can be increased with shorter TL_s, showing a raised possible oscillation frequency. In the final design, the length of TL_s is ~1000 µm (C_s ~ 18.5 fF) with a simulated R_{neg} of ~ -40 Ω, which is sufficient for meeting the oscillation starting condition. An octagon-like tank inductor L_T is designed for saving the chip area which consumes only 0.26 × 0.27 mm^2. At the center node of L_T, the signal from the balanced branch is combined, where out-of-phase f_0 is canceled by each other and in-phase 2nd harmonic frequency ($2f_0$) is combined. A quarter wavelength transmission line at $2f_0$ with a bypass capacitor is used for providing the drain bias voltage, and DC block C_D at $2f_0$ is used in the output path. The LC circuit also features a high-pass filter which further suppresses the f_0 leakage by ~ 8 dB.

Optimization of the transmission line structure is another critical issue for the circuit operating at such high frequencies. The SiC substrate in the GaN technology is 100-µm thick with a relative dielectric constant of 9.7, which can be referred to as an "electrically thick" substrate at the desired operating frequency [7]. Implementing the circuit using the microstrip line would introduce high radiation loss. Therefore, the CPW structure is used for the proposed design. Fig. 5(b) compares

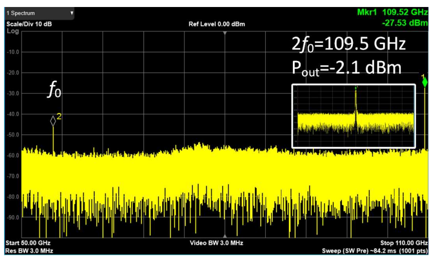


(a)

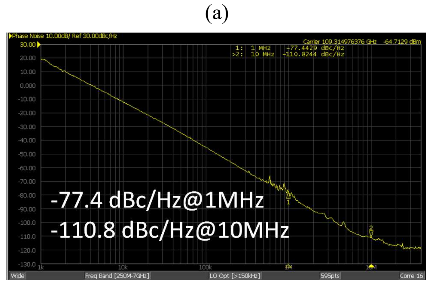


(b)

Fig. 5. (a) Negative resistance of the balanced core and the equivalent capacitance C_s of TL_s versus the length of TL_s (b) Return loss and insertion loss of the two CPWs with and without the TWVs.



(a)



(b)

Fig. 6. Measured (a) spectrum and (b) phase noise of the proposed oscillator.

the reflection coefficient and the insertion loss of the GCPW with and without the TWVs, at the lengths of 2λ at 110 GHz, respectively. With below -10 dB reflection loss designed at the input and output, the GCPW with TWVs exhibits a 1.36-dB smaller loss than that of the CPW with the floating ground at 110 GHz. Note that the spacing between TWVs is designed based on both design rules and the analytical model from [8], and the airbridges using layer metal 2 are utilized to balance the electrical potential in the discontinuity.

III. Measured Results and Discussion

The chip was measured on-wafer up to 110 GHz using the spectrum analyzer (Keysight N9041B UXA) for oscillation

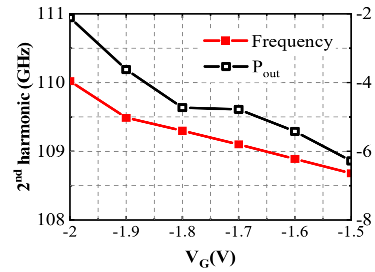


Fig. 7. Measured output frequency and output power versus the gate bias voltage.

frequency of the fundamental and the 2nd harmonic, and the signal source analyzer (Keysight E5052A) with downconverter (Keysight E5053A) and 110-GHz harmonic mixers (Keysight 11970W) was used for phase noise measurement. Under a power consumption of 295.5 mW, the measured output signal frequency is 109.5 GHz with a power level of -2.1 dBm after calibration of cable loss, as shown in Fig. 6 (a). Fig. 6 (b) shows the measured phase noise, which is -110.8 dBc/Hz at a 10-MHz offset. Fig. 7 shows the frequency tuning range and output power of the 2nd harmonic frequency as V_G varies from -1.5 to -2 V. It should be emphasized that a higher oscillation frequency can be obtained, while it is limited by the measurement equipment. To the best of the authors' knowledge, this work reports the highest oscillation frequency based on a 0.15-μm GaN HEMT technology. Table 2 also compares the reported sub-THz oscillators using GaN HEMTs with different gate lengths. This work exhibits comparable oscillation frequency with high f_0/f_T and f_0/f_{max} ratio normalized by the individually adopted technology.

IV. Conclusion

This paper presented a sub-THz push-push balanced Colpitts oscillator up to 110 GHz based on 0.15-μm GaN HEMT technology. The in-house 3-terminal model was built to design the source capacitor for the Colpitts feedback capacitor and enhancement of negative resistance. The GCPW transmission line configuration was adopted to minimize signal loss. By using the relatively small parasitic capacitor for the feedback path, the oscillator can achieve high frequency and low power operation simultaneously. The measured results demonstrated the highest operating frequency compared with other reported works using GaN HEMT with the same gate length, which is suitable for the emerging applications of millimeter-wave radar imaging and sensing systems.

Table 2. Performance Comparison with Prior Sub-THz GaN Oscillators

Refs	GaN HEMT Tech.	Topology	Frequency (GHz)	f_0/f_T	f_0/f_{max}	P_{out} (dBm)	P_{DC} (mW)	PN (dBc/Hz)
[4]	60 nm	Push-push	180.6*	0.47	0.36	9.3	920	-88.2@10MHz
[5]	60 nm	Common-gate Colpitts	84	0.44	0.34	-0.67	340	-120@10MHz
[8]	100 nm	Single-end	89.2	1.11	0.44	10.2	650	-90.2@1MHz
This work	150 nm	Push-push balanced Colpitts	109.5*	1.71	0.4	-2.1	295.5	-77.4@1MHz -110.8@10MHz

*2nd harmonic output.

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