A 1–42 GHz GaN Distributed Amplifier With Adjustable Gain by Voltage-Controlled Switch

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***Abstract*— A 1–42 GHz gain-variable distributed amplifier is presented in the letter using a 0.13-μm gallium nitride (GaN) process. The amplifier can achieve a gain tuning range of about 3 dB over the entire frequency band by voltage-controlled switching. The chip area of the amplifier is about 1.9 × 1.1 mm^2. The average output power of the amplifier is greater than 27.5 dBm over the entire bandwidth. A wider gain tuning range can be achieved by adding more voltage-controlled switches.**

***Index Terms*— Adjustable gain, distributed amplifier, gallium nitride (GaN), switch, ultrawideband.**

I. Introduction

AMPLIFIERS with ultrawide bandwidth and high output power are playing more and more important roles in wide-band wireless systems (for example see [1]–[5] and references therein). In order to meet the required specifications, distributed amplifiers with a wide tuning range have drawn much attention [6]–[8].

Distributed amplifiers with tuning circuits have been popularly implemented in CMOS technologies with very successful performances as drivers for various power amplifiers (PAs). It is the trend to have higher output power levels for those PAs, which requires higher input power levels of those PAs because of the concerns on the overall power-consumptions and the efficiencies. However, the input signals of PA drivers, specifically distributed amplifiers always have similar input levels as old days, which implies higher outputs for the distributed amplifiers. Due to the stability concern, a distributed amplifier cannot adopt too many stages; alternatively, less stages with higher output levels are desired.

It is well known that gallium nitride (GaN) HEMT can have higher power levels, in this letter, a distributed amplifier with resistive-switched HEMT before the last stage has been implemented in a 0.13-μm GaN technology. The gain tuning of this variable gain distributed amplifier is achieved by adjusting the voltage-controlled switch. The amplifier has a 3 dB bandwidth of about 50 GHz and a chip area of 1.9 × 1.1 mm^2. The measured results show that with a bias voltage of 0 to −6 V applied to the switch, the gain control range from 1 to 42 GHz bandwidth is close to 3 dB, and the input standing wave is improved over the entire operating frequency range.

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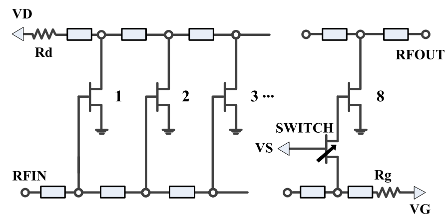

Fig. 1. Simplified schematic of the switch-controlled distributed amplifier circuit.

II. Process and Circuit Design

A. Process

The amplifier is designed using GaN on silicon carbide process, providing GaN transistors with 0.13 μm mushroom gate defined by electron beam lithography. The transistor demonstrates an excellent performance with a cutoff frequency of $f_T = 80$ GHz and a maximum frequency of $f_{\max} = 180$ GHz. The amplifier utilizes eight 4 μm × 25 μm HEMTs in circuit design, which have a breakdown voltage of above 50 V.

B. Circuit Design

The simplified schematic of the amplifier circuit is shown in Fig. 1. In consideration of maximum bandwidth, the uniform gain and output power over the whole frequency band, eight four-finger 25 μm gate width GaN HEMTs operating at 18 V with the quiescent current of 150 mA/mm.

In the circuit, microstrip lines are loaded periodically with the GaN HEMTs, forming the artificial gate and drain transmission lines. To match the 50-Ω terminations of the microwave systems, the characteristic impedance of the drain lines is chosen to be 50 Ω for simplicity. Furthermore, each drain line or gate line between two adjacent HEMTs was selected to be identical. A radio frequency (RF) signal applied at the input port transmits along the gate line to another end and is absorbed by the gate terminal resistance R_g. The input signal captured by the GaN gate circuits is transferred to the drain transmission line by the transconductance of the GaN HEMTs. On the one hand, when the phase velocity at the gate line is identical to that at the drain line, the forward traveling signals on the drain line add. On the other hand, the backward traveling signals are absorbed by the drain terminal resistance R_d of 50 Ω.

The difference from a conventional distributed amplifier is that a switch-mode GaN HEMT with variable resistance controlled by an external bias is adopted as a switch in the circuit following the eighth transistor, which plays an essential

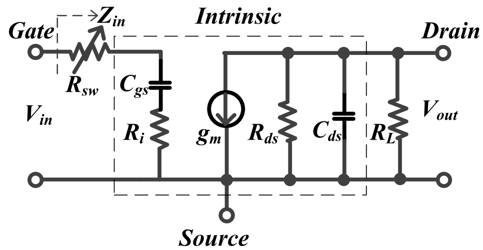

Fig. 2. Simplified equivalent schematic of the eighth GaN HEMT circuit with a switch.

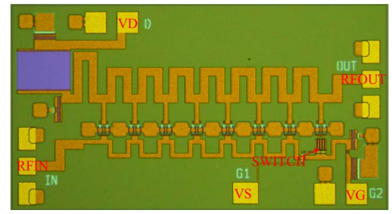

Fig. 3. Die microphotograph of the fabricated distributed amplifier.

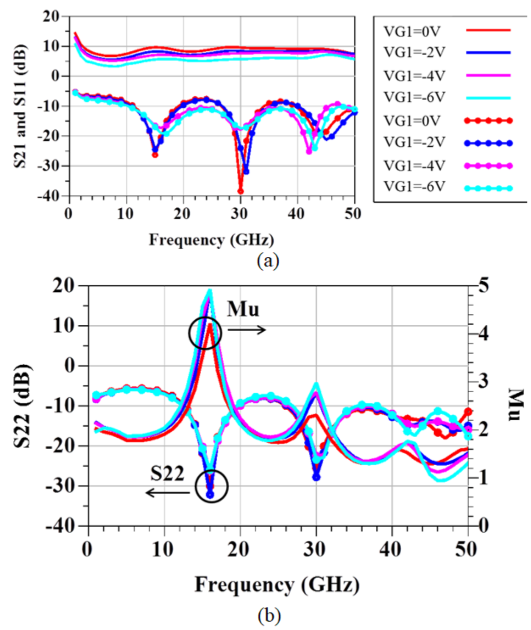

Fig. 4. Measurement results at different biases. (a) S_{11} (marked lines) and S_{21} (solid lines). (b) S_{22} (marked lines) and Mu (solid lines).

role in control gain. This switch can partly turn on or off the eighth transistor, attributed to the whole gain. Besides, a tuned bias voltage of the switch responds to a variational resistance connected to the transistor, resulting in shifted matching status in the traveling-wave structure. It follows that a different gain of the amplifier is obtained. The explanation is as follows.

The simplified equivalent schematic of the eighth GaN HEMT circuit with a switch is as shown in Fig. 2, the voltage gain of the eighth HEMT is

$$G_{v8} = \frac{V_{\text{out}}}{V_{\text{in}}} = \frac{g_m\left(R_{\text{ds}} \parallel R_L \parallel \frac{1}{j\omega C_{\text{ds}}}\right)}{1 + j\omega C_{\text{gs}}(R_{\text{sw}} + R_i)} \tag{1}$$

where g_m is the transconductance, R_i and R_{ds} are input and output resistance, respectively, R_{sw} represents the variable resistance of the switch, R_L is load impedance, C_{gs} and C_{ds} are the input gate–source capacitance and output drain–source capacitance, respectively. From (1), the smaller R_{sw} is, the higher G_{v8} is. When the switch operates from ON-state to OFF-state, with R_{sw} getting larger and larger, G_{v8} tends to be zero.

Also, in a proper operating regime, the gain of distributed amplifiers G is proportional to n^2 for simplicity [2]

$$G \simeq \frac{g_m^2 n^2 Z_0^2}{4} \tag{2}$$

where n is the number of cells used in the circuit and Z_0 is the input and output characteristic impedance. When the switch is turned on, it is a very small resistance and $n = 8$, corresponding to a maximal G; when the switch is turned off, it is a very large resistance and $n = 7$, corresponding to a minimal G; when the switch is at the state between the ON-state and the OFF-state, G is in the middle.

In addition, the input impedance of the eighth HEMT is

$$Z_{\text{in}} = R_{\text{sw}} + \frac{1}{j\omega C_{\text{gs}}} + R_i. \tag{3}$$

This indicates that the switch's introduction leads to the transformation of the input impedance, hence, the input standing wave changes.

III. Measurements and Discussions

The photograph of the fabricated distributed amplifier is shown in Fig. 3. The die dimensions, including testing pads, are only 1.9 × 1.1 mm^2. The dc bias is applied through RF probes with external bias tees. Since there is a voltage drop in the drain terminal resistance of 50 Ω, the drain bias point increases to 24 V.

The amplifier was measured via on-wafer probing driven by setting $V_S = 0$ to -6 V, $V_G = -2$ V, and $V_D = 24$ V. V_S denotes the applied switch voltage. As shown in Fig. 4(a), when the switch is turned on ($V_S = 0$ V), the amplifier has a measured small-signal gain S_{21} of about 8 dB ± 1.5 dB from 2 to 50 GHz, corresponding to input–output return loss around -10 dB. This indicates that the distributed amplifier proposed in this letter successfully achieves the expected design results and high gain flatness over the entire frequency range. However, at lower frequencies below 2 GHz, there is a larger fluctuation in the gain, probably caused by the insufficient decoupling of dc needles during the S-parameter measurements [6], [10]. The use of external large value dc decoupling capacitors in RF components can improve gain flatness at the low end of the frequency range.

Also, with a controlled voltage of the applied switch from 0 to -6 V, the small-signal gain S_{21} decreases gradually, and about 3 dB gain decrease over 1–42 GHz is acquired, which is a benefit to broadband systems with flexible and large gain dynamic range. With the application of switches, a wider range of gain tuning can be achieved without additional attenuators, reducing chip area, system complexity, and cost and achieving higher gain flatness. In higher frequency, the loss of the artificial transmission line increases causes a slighter contribution to the gain for the far transistor, which results in smaller gain tuning capability. The maximum gain movement

TABLE I
PERFORMANCE COMPARISON WITH PUBLISHED GaN DISTRIBUTED AMPLIFIER

Reference (#)	Frequency (GHz)	BW[1] (GHz)	Gain[2] (dB)	Psat[3] (dBm)	Die Size (mm^2)	Circuit Topology	Technology (μm)
[9]	0.1-45	45	10	~28@35GHz	2.8	Cascode	0.15
[11]	1-50	49	5.2	~22@4GHz	2.6	Single-stage	0.2
[11]	2-32	30	12	~30@4GHz	4.4	Single- stage (Dual-gate)	0.2
[12]	8-42	34	6	~25@38GHz	3.5	Single-stage	0.1
[12]	8-42	34	14	~27@42GHz	6.6	Single- stage (Dual-stage)	0.1
This work	**1-50**	**49**	**8**	27~30@1~42GHz	**2.1**	**Single-stage**	**0.13**

[1]BW is the approximate 3 dB frequency band; [2]Gain is the average small signal gain; [3]Psat is the saturated output power.

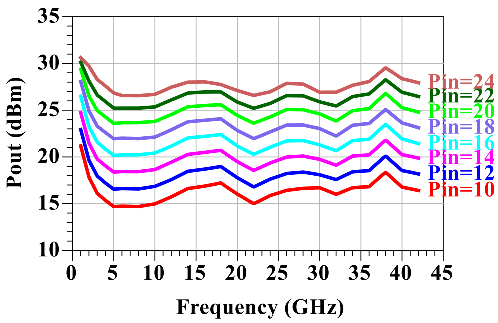

Fig. 5. Measured CW power (solid lines) for swept-source power.

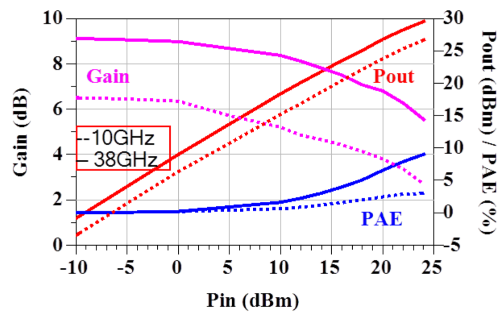

Fig. 6. Measured CW power data of the amplifier at 38 GHz (solid lines) and 10 GHz (dot lines).

reaches more than 4 dB at 15 GHz due to the contribution to the eighth HEMT and the significant variation of the input matching. In addition, gain flatness and input standing waves are typically better in the 1–42 GHz range with a bias V_S of −4 V than at 0 V. It is the changed bias point that leads to the switch's variable resistance resulting in the changed input match. It is noticed that at a switching bias of −6 V when the switch is totally OFF, the gain variation is more obvious. As shown in Fig. 4(b), the amplifier is stable during gain variation over the entire frequency range with a controlled voltage of the applied switch from 0 to −6 V.

The conventional cascoded distributed amplifier is very sensitive to changes in gate voltage because it achieves gain tuning by adjusting the bias of gate 2 [9], which makes it more prone to self-excitation. Therefore, the new amplifier proposed in this letter has higher stability than the conventional cascoded distributed amplifier. In addition, the chip area is relatively reduced by 25% compared with the chip area of the traditional cascoded distributed amplifier [9].

Large signal continuous wave (CW) output power (P_{out}) with available input power (P_{in}) ranging from 10 to 24 dBm in 2 dBm steps over 1–42 GHz were measured, and Fig. 5 plots the P_{out} versus both P_{in} and frequency. The bias condition is $V_S = 0$ V, $V_G = -2$ V, and $V_D = 24$ V. The large-signal measurements show a $P_{\text{out}} > 30$ dBm at 1 GHz with $P_{\text{in}} = 24$ dBm. The average power gain is about 3.5 dB in the measured frequency range at $P_{\text{in}} = 24$ dBm. In the millimeter-wave (mm-wave) band, the maximum power reaches 29 dBm at 38 GHz.

The measured CW large signal gain, output power, and power-added efficiency (PAE) of the distributed amplifier at 38 GHz and 10 GHz with 24 V drain-bias, −2 V gate-bias, and 0 V switch-bias are shown in Fig. 6. The amplifier acquires a PAE of 9% and output power of 29 dBm at 38 GHz while a PAE of 3% and an output power of 27 dBm at 10 GHz, respectively at a source power of 24 dBm. However, the amplifier's output power measured in Fig. 6 did not reach saturation due to the lack of a larger output power signal source.

Furthermore, one or more switches can be employed before any transistor, accordingly influencing input–output match by altering the switch bias point. A careful design of the matching network can improve the gain and input–output standing wave performances. The inserted switches in the conventional distributed circuit can significantly raise the dynamic range of the gain for such a broadband amplifier.

Finally, the comparison of this work to previously published GaN distributed amplifiers is afforded in Table I. The design presented here possesses a high gain among the single-stage (except for dual-gate or dual-stage) amplifiers covering over 30 GHz bandwidth with the smallest overall die size.

Additionally, this amplifier exhibits good power capability. What's more, this design can provide a certain gain control capability while others did not mention it. This gain-controlled function may be flexible and helpful in practical application.

IV. CONCLUSION

This letter presents a 1–42 GHz gain-variable distributed amplifier fabricated using a 0.13-μm GaN process, which achieves a gain tuning range of approximately 3 dB with just a voltage-controlled switch. Therefore, in this work, more design efforts had been spent in considering the gain-flatness and gain control. Moreover, it is possible to achieve a wider gain tuning range by increasing the number of switches.

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