X-Band High Power GaN SPDT MMIC RF Switches

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***Abstract* — This paper describes the design results and measured performance of three different high power, low loss and high isolation GaN high electron mobility transistor (HEMT) based single-pole double-throw (SPDT) RF switches. Three different topologies were employed to design the proposed switches. The SPDT MMIC switches were developed with coplanar waveguide (CPW) GaN-HEMT technology to operate in X-Band. The measured performance showed that the switches have typical insertion loss of better than 2 dB, higher than 30 dB isolation with better than 10 dB return losses.**

***Keywords* — coplanar waveguide, GaN, high power, MMIC, RF switch, SPDT, X-Band.**

I. INTRODUCTION

The Gallium Nitride (GaN) on Silicon Carbide (SiC) HEMT technology is suitable for high power applications with its excellent electrical and thermal properties. High breakdown voltage (V_{BD}) property utilizes the usage of high control voltage levels to allow higher voltage swing on the shunt transistor during the off-state. High current density property makes the usage of series transistor feasible under high RF current swing during the on-state.

High power RF switches are required in many applications such as radars, base stations and T/R modules. Therefore, an SPDT switch has to be low loss during the on-state to transmit the power and has high isolation during the off-state to protect the circuitry. Besides many applications require small foot-print with minimal weight and power consumption. Although the PIN diode switches can handle high power, they consume significant amount of DC power while GaAs FET switches consume low amount of DC power, they are limited with RF power handling capability [1], [2]. On the other hand, mechanical switches can handle high RF power, but they are heavy, large in size, and have slow switching speed.

GaN-on-SiC HEMT technology offers SPDT MMIC RF switches that have high power handling, low insertion loss, high isolation and fast switching speed. These properties make them very attractive for the systems that require superior performance. Therefore, different types of SPDTs were introduced utilizing GaN HEMT technology for various operation bands to overcome the drawbacks of PIN diodes, GaAs FETs and mechanical switches [2] – [11].

In this paper, GaN HEMT based switches with different topologies that have less than 2 dB insertion loss, more than 30 dB isolation, more than 40 dBm power handling and less than 40 ns switching speed are introduced. The performance summary is given by comparing them with the state-of-the-art GaN SPDT MMIC switches

II. GAN MMIC TECHNOLOGY

The SPDT switches proposed in this paper have been fabricated with the I.D. Bilkent University Nanotechnology Research Centre (NANOTAM) coplanar waveguide (CPW) GaN-on-SiC HEMT technology. The GaN-HEMT technology consists of full CPW MMIC production capabilities with 300 µm substrate thickness, epi. layer sheet resistance of 350 Ω/□, ~0.25 Ω.mm contact resistance, 300 pF/mm^2 MIM capacitors, 15 Ω/□ NiCr TFRs, and two levels of interconnect metal including air bridge.

The switch HEMT was developed with 0.3 µm gate technology with a typical current density of ~1.2 A/mm and ~330 mS/mm transconductance [7].

III. SWITCH HEMT CHARACTERIZATION

The proposed SPDT switches were designed based on an extracted transistor model of the unit switch HEMT represented in Fig. 1. As shown in Fig. 1, an isolation layer resistor was added to gate port to improve the isolation between the DC path and the RF path. The resistor at the gate was grounded to make the characterization of the transistor easier. This configuration makes it possible to measure the performance with two ports instead of three ports.

A HEMT has a low ON-state resistance and high OFF-state capacitance between the input and the output. Therefore, ON-state performance of the transistor was measured by applying 0 V to both ports and OFF-state performance was measured by applying +30 V to both ports.

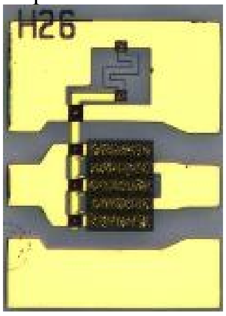


Fig. 1. Unit GaN switch HEMT

Measured performance and modelling results showed that the transistor has ON-state resistance (R_{ON}) of 2.2 Ω.mm and

OFF-state capacitance (C_{OFF}) of 0.3 pF/mm. These results showed a figure-of-merit of 241 GHz based on (1).

$$FOM = \frac{1}{2 \times \pi \times R_{ON} \times C_{OFF}} \qquad (1)$$

IV. SPDT MMIC SWITCH DESIGN APPROACH

The design goal was to achieve reflective X-Band switches with insertion loss (*IL*) better than 2 dB and 25 dB isolation at worst and better than 10 dB return loss (*RL*). In order to achieve the goals a switch HEMT model was extracted using the unit switch HEMT represented in Fig. 1.

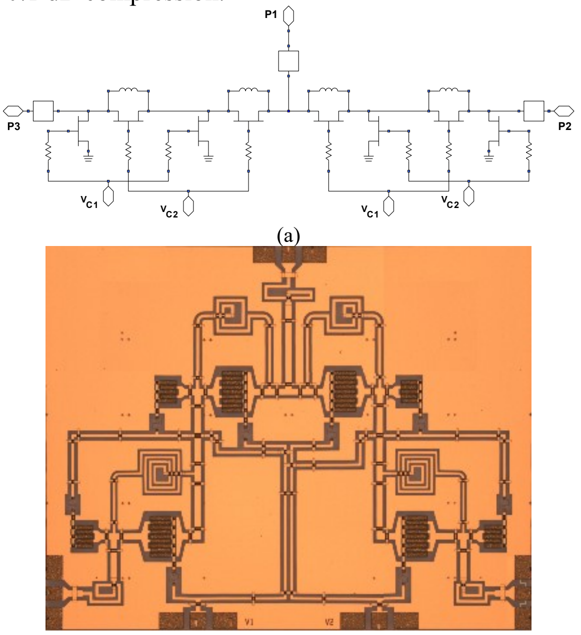
Three SPDT MMICs were designed utilizing tuned SPDT, quarter-wave transformer based SPDT and series-shunt-shunt SPDT topologies in a proper way to satisfy the requirements. The circuit schematics and microphotographs of the tuned SPDT (SPDT-T1), quarter-wave transformer based SPDT (SPDT-T2) and series-shunt-shunt SPDT (SPDT-T3) represented in Fig. 2, Fig. 3 and Fig. 4 respectively.

The on-state and off-state power handlings of the SPDTs calculated using (2) and (3) respectively [9]. The on-state power handling is limited by the maximum channel current (I_{MAX}), and the off-state power handling is limited by the breakdown voltage (V_{BD}). Typical values for I_{MAX} at V_{ds} = 0 V and V_{BD} are 1 A/mm, and 70 V respectively with -4.2 V pinch-off voltage (V_P).

$$P_{H-ON} = \frac{I_{MAX}^2 Z_0}{2} \qquad (2)$$

$$P_{H-OFF} = \frac{(V_{BD} - V_P)^2}{2Z_0} \qquad (3)$$

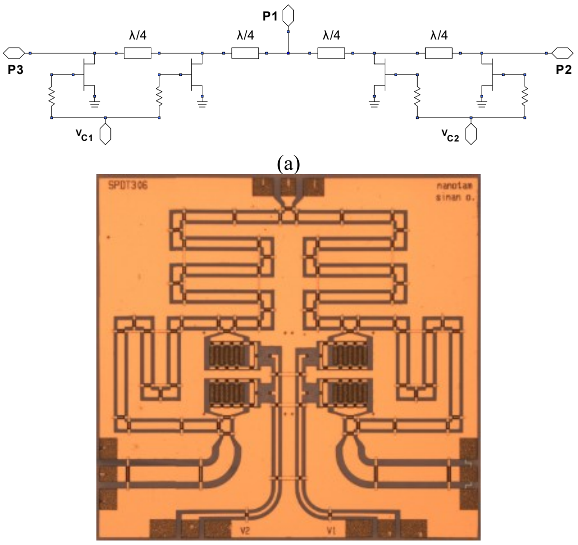
The sizes of the transistors were optimized with simulations in a way to reach the requirements and 10 W power handling with 0.1 dB compression.



(a)

(b)

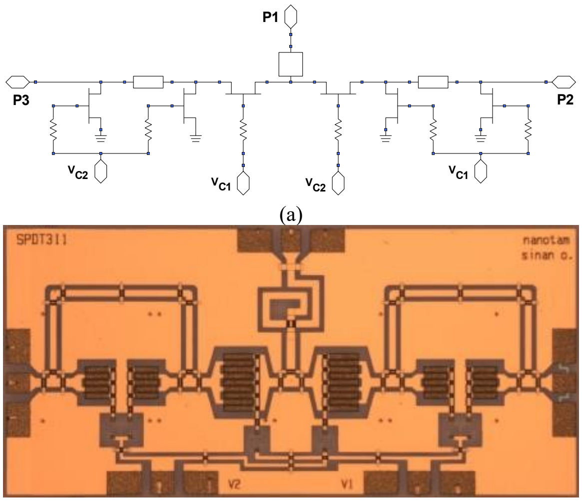
Fig. 2. (a) Schematic and (b) microphotograph of the SPDT-T1 (Die Size: 2.96 × 2.34 mm^2)



(a)

(b)

Fig. 2. (a) Schematic and (b) microphotograph of the SPDT-T2 (Die Size: 2.14 × 2.0 mm^2)



(a)

(b)

Fig. 4. (a) Schematic and (b) microphotograph of the SPDT-T3 (Die Size: 2.46 × 1.15 mm^2)

V. MEASURED PERFORMANCE

MMIC SPDT switches were characterized on-wafer with RF probes that have ground-signal-ground (G-S-G) configuration and 150 µm pitch.

A. Small-Signal Characterization

Small-signal measurements are performed with a VNA: measurement vs. simulation results are represented in Fig. 5 to Fig. 7 for SPDT-T1, SPDT-T2, and SPDT-T3 respectively. Moreover, comparison of *IL* and isolation performance of three SPDTs are given in Fig. 8.

The measurement results show a good agreement with the simulations. SPDT-T2 and SPDT-T3 have better than 2 dB IL up to 12 GHz and SPDT-T1 has slightly worse *IL* between 10 GHz and 12 GHz. All SPDTs have better than 10 dB *RL* and better than 25 dB isolation up to 12 GHz. Moreover, SPDT-T1 and SPDT-T3 have better than 30 dB isolation.

Since SPDT-T3 has the least amount of series components in the conduction path, it has less than 1.2 dB *IL* from DC to 12 GHz while the *IL* performance of SPDT-T1 and SPDT-T2 are typically 2.0 dB and 1.7 dB respectively. According to the 2 dB *IL* limit, SPDT-T1 can operate between 4 – 10 GHz, SPDT-T2 can operate between 3 – 13 GHz and SPDT-T3 can operate from DC to 14 GHz.

Due to lack of series transistor in SPDT-T2, the isolation is worse in comparison with SPDT-T1 and SPDT-T3. On the other hand, SPDT-T1 has series transistors and the off-state capacitances were resonated by parallel inductors to improve the isolation. Therefore, better than 50 dB isolation is achieved in X-Band and more than 40 dB isolation is observed from 4 GHz to 12 GHz.

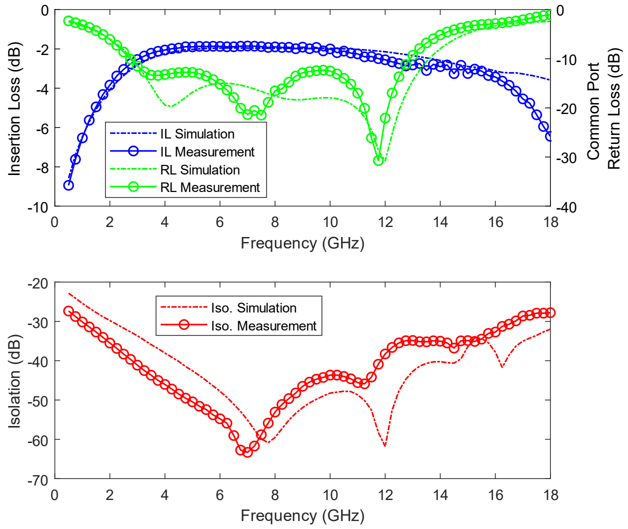


Fig. 5. Small-Signal measurement vs. simulation results of SPDT-T1

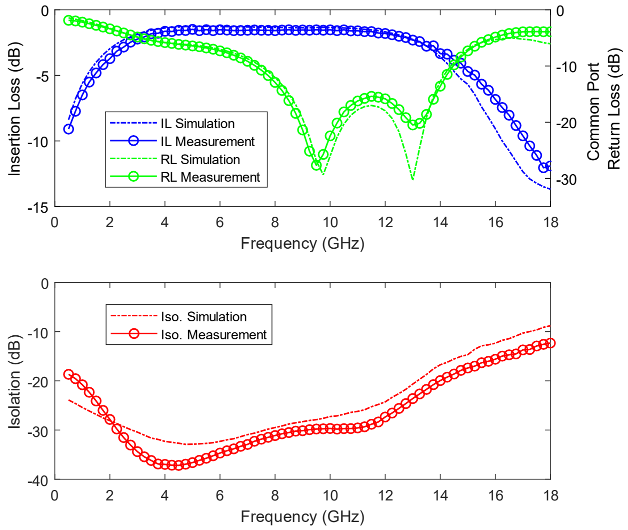


Fig. 6. Small-Signal measurement vs. simulation results of SPDT-T2

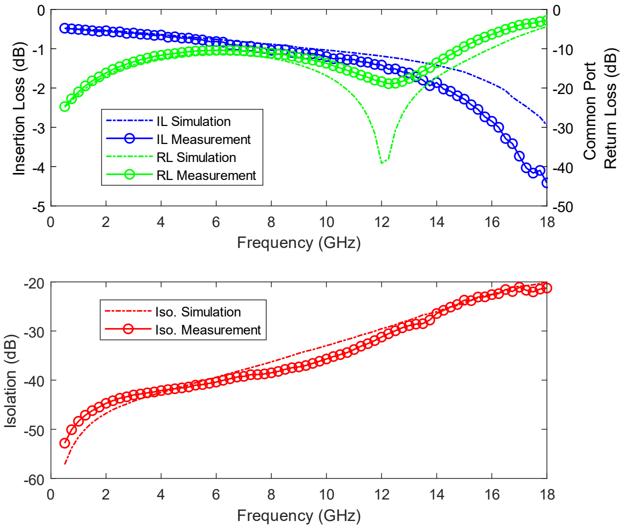


Fig. 7. Small-Signal measurement vs. simulation results of SPDT-T3

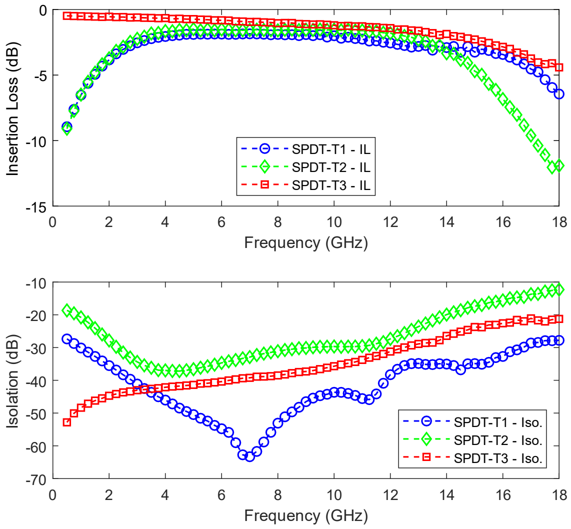


Fig. 8. Comparison of Insertion Loss measurement results and Isolation measurement results of the SPDTs

B. Large-Signal Characterization

Large-signal measurements were performed at 12 GHz with CW-mode input power from 26 dBm to 40 dBm and results are represented in Fig. 9. SPDT-T1 and SPDT-T3 can handle 40 dBm input power with a compression level of ~0.1 dB whereas SPDT-T2 can handle same power level with ~0.15 dB compression.

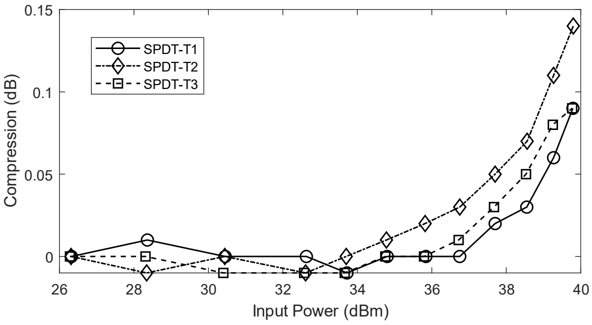


Fig. 9. Power sweep measurements of SPDTs at 12 GHz

C. Switching Time Characterization

To control the SPDT states, a driver circuit was developed and used for switching time measurements. Switching time was measured by using a square law detector and an oscilloscope. ON-time is calculated as the time difference between 50% of the transition of the control signal to 90% of the detected RF output when the switch state is changed from OFF-state to ON-state as shown in Fig. 10. OFF-time is calculated as the time difference between 50% of the transition of the control signal to 10% of the detected RF output when the switch state is changed from ON-state to OFF-state as shown in Fig. 10.

The measurement results showed an OFF-time better than 60 ns and ON-time better than 100 ns including the driver propagation delay for SPDT-T3. The propagation delays were measured as ~20 ns and ~70 ns for OFF-time and ON-time measurements respectively. If the propagation delays are subtracted from the switching speed measurements, then SPDT-T3 can switch from ON-state to OFF-state in less than 40 ns and switch from OFF-state to ON-state under 30 ns.

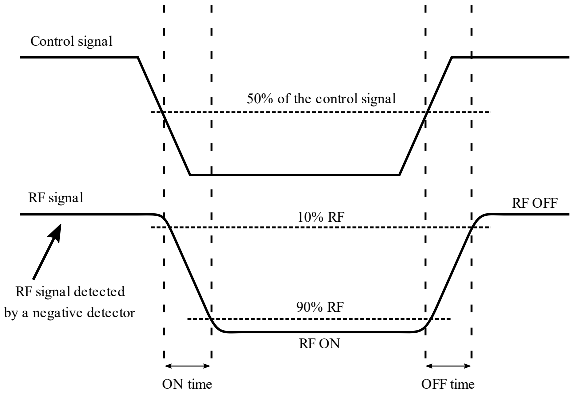


Fig. 10. Timing diagram of switching time of a switch

Performance summary of the measurements are given in Table 1 in comparison with the state-of-the-art GaN SPDTs.

VI. CONCLUSION

In this paper, three MMIC SPDT RF switches, based on CPW AlGaN/GaN HEMT on SiC substrate technology, with different topologies for X-Band applications are represented. The proposed RF switches have demonstrated more than 10 W RF power handling performance with better than 2 dB insertion loss, better than 30 dB isolation and return loss of better than 10 dB. Moreover, demonstrated SPDT-T3 switch has better than 40 ns switching speed which is critical for many applications.

Table 1. Comparison of the state-of-the-art X-Band SPDT RF Switches

	Freq. (GHz)	*IL (dB)*	*Isolation (dB)*	*RL (dB)*	*$P_{0.1dB}$ (dBm)*	*Sw. Speed (ns)*
[4]	8 – 12	≤ 2.0	≥ 35	≥ 12	P_{1dB}=35	N/A
[6]	DC – 12	≤ 1.0	≥ 30	≥ 14	36 at 12 GHz	N/A
[10]	8 – 12	≤ 1.2	≥ 37	≥ 13	39 at 12 GHz	N/A
[11]	8 – 12	≤ 3.5	≥ 35	≥ 10	44*	N/A
SPDT-T1	4 – 10	≤ 2.0	≥ 40	≥ 13	40 at 12 GHz	not measured
SPDT-T2	3 – 13	≤ 1.7	≥ 25	≥ 15 (in X-Band)	39 at 12 GHz	not measured
SPDT-T3	DC – 14	≤ 1.2 up to 12 GHz	≥ 30	≥ 11	40 at 12 GHz	≤ 40

* Measurement frequency and compression level is not specified.

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