Monolithic AlGaN/GaN HEMT SPDT switch

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Abstract— **In this summary we present design and experimental results of a monolithic L/S band SPDT switch based on AlGaN/GaN HEMT's. The switch was measured to have 0.87, 0.96, 1 dB insertion loss and 46, 42 and 41 dB isolation at 0.9, 1.8 and 2.1 GHz respectively. The switch also shows linear performance for the power levels up to 1 Watt in the insertion mode and more than 2 Watts in the isolation mode.**

Index Terms— **AlGaN/GaN HEMT, MMIC, switch.**

I. INTRODUCTION

AlGaN/GaN HEMT is a new developing technology primarily targeted for high power applications at RF, microwave and millimeter-wave frequencies. Owing largely to high electrical breakdown field, high electron sheet charge density and availability of a semi-insulating bulk substrate material, SiC, with high thermal conductivity and reasonable atomic lattice mismatch, AlGaN/GaN HEMT's have been shown to be capable of handling, amplifying and delivering significantly larger power density signals than the currently used MMIC technologies. These unique performance characteristics has been exploited to demonstrate various monolithic, hybrid and flip-chip circuits based on AlGaN/GaN HEMT's. These circuits include broad-band amplifiers [1], [2], amplifiers for wireless infrastructure applications [3], fixed frequency and voltage-controlled oscillators [4], [5].

As the technology gradually matures, the set of possible circuit application broadens. It has been recognized for some time that wide-bandgap devices can provide certain advantages in the design of high-power RF and microwave switches with added benefit of large ESD thresholds [6]. To this effect, Drozdovsky et al [7] have developed small- and large-signal switch models for AlGaN/GaN HEMT's. Koudimov et al [8] have demonstrated high-power capability in switching operation of a discrete AlGaN/GaN MOSHFET. Shealy et al [6] have presented hybrid switches based on AlGaN/GaN HEMT operating at RF frequencies.

A monolithic L/S-band SPDT switch with high isolation and power is presented in this work.

II. DESIGN

Monolithic AlGaN/GaN HEMT single pole -double throw switch has been designed using linear simulation to predict small-signal insertion loss and isolation and non-linear simulation using Statz large-signal model to estimate power handling and linearity characteristics. The design goals were: bandwidth- DC to 3 GHz, insertion loss < 1 dB, isolation better than 40 dB, $P_{1dB} \approx 1$Watt. The goals' selection was dictated by a desire to demonstrate that GaN-based switches can simultaneously achieve reasonably high power handling capability without sacrificing the isolation and the insertion loss. On of the common ways used to improve power performance of GaAs-based switches is to increase the transistor periphery, which negatively affects the isolation due to an increase in off-capacitance. Most reported high-power GaAs switches demonstrate isolation of less than 30 dB [9], [10].

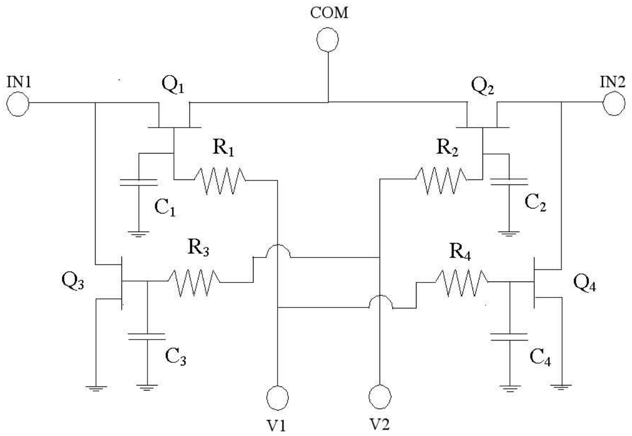

Fig. 1. Schematic of the AlGaN/GaN HEMT MMIC SPDT switch.

The switch design is based on a circuit configuration, shown in figure 1, consisting of two series and two shunt transistors. First, transistors' periphery has been selected to satisfy the power design requirements. Since the breakdown voltage in an AlGaN/GaN HEMT is many times larger than the pinch-off voltage, switch's power handling is set by the open-channel current limit of a transistor. Therefore, to satisfy design's power requirements, total gate width of the series FETs has to be chosen appropriately. Assuming sinusoidal current and voltage waveforms, the required amplitude of the current swing in a series transistor can be estimated from equations 1 - 3.

$$P_{out_{max}} = \frac{\Delta V}{2\sqrt{2}}\frac{\Delta I}{2\sqrt{2}} = \frac{\Delta V \Delta I}{8} \tag{1}$$

$$\Delta I = \frac{8P}{\Delta V} = \frac{4P}{V_{knee}} \tag{2}$$

$$I_{max} = \frac{\Delta I}{2} = \frac{2P}{V_{knee}} \tag{3}$$

Using typical values of knee voltage V_{knee} and open-channel current density I_{max} of 5 V and 1 A/mm respectively, the gate width of series FET's required to obtain P_{1dB} of 1 W is calculated to be equal to 400 μm.

In the switch schematic, series HEMTS Q_1 and Q_2 are controlled by two corresponding control voltages V_1 and V_2, one of which has zero value and another has a negative value larger than the pinch-off of the transistors. Under these conditions, one of the RF inputs ($IN1$ or $IN2$) are connected to the common port COM through a low value of the corresponding HEMT's on-resistance, while the other RF input is isolated from the COM port by the large value of the drain-source resistance in the pinch-off mode. Without adding any additional circuit components, the switch configuration with the series transistors only (with total gate width of 400 μm) will exhibit, according to linear simulation, isolation at 3 GHz of only 21 dB, which would not satisfy the design requirements. The low value of the isolation is mostly determined by the finite value of the HEMT's drain-source resistance in the subthreshold mode. Due to this residual conductance, some RF signal leakage occurs through the pinched-off transistor. The isolation can be improved by decreasing the total gate width. This, however, would adversely affect both the insertion loss and the power handling.

A common circuit approach to improve switch small-signal characteristics is to add two shunt HEMT's Q_3 and Q_4 which are connected to the same control voltages as the series transistors, V_2 and V_1 respectively. In a case when V_1 and V_2 are set to zero and below pinch-off respectively, Q_1 and Q_4 are open while Q_2 and Q_3 are shut. The isolation between $IN2$ and COM (as well as with $IN1$) is considerably increased because the Q_4 provides low-resistance path to ground for a signal applied to $IN2$. This improvement in the isolation also helps to slightly decrease the insertion loss in the other arm of the switch. Further performance improvement was achieved by optimizing values of series resistors and shunt capacitors in DC control lines, primary purpose of which is to prevent any oscillations. Linear simulation predicted the insertion loss of 0.9 dB and the isolation of 43 dB at 3 GHz. An attempt has been made to make the switch terminated (absorptive), that is to minimize return loss in the isolation mode. This can be accomplished by adding resistors in series with the shunt FETs Q_3 and Q_4. However, this modification would significantly reduce the isolation (to get 10 dB return loss, the isolation would have to be decreased by 20 dB), thus making the change not prudent.

The final design is symmetric so the performance is expected to be equivalent for both RF inputs.

III. EXPERIMENTAL RESULTS

The fabricated circuit has dimensions 1.6 x 1.0 mm, and is depicted in figure 2.

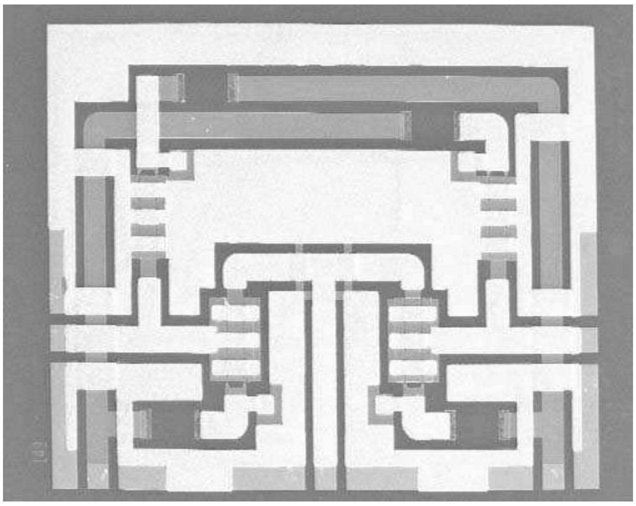

Fig. 2. SEM image of the fabricated AlGaN/GaN HEMT MMIC SPDT switch.

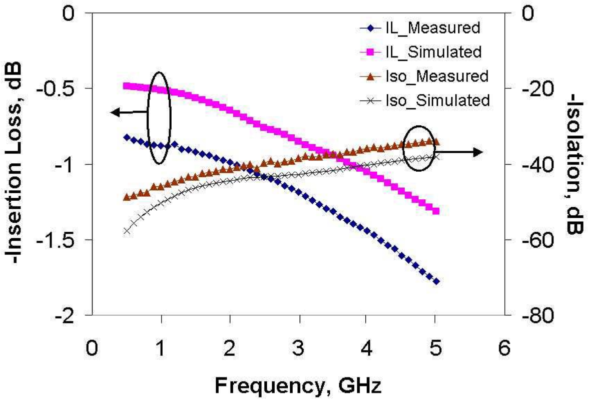

Fig. 3. Comparison of measured and simulated inserion loss (IL) and isolation (Iso) of AlGaN/GaN HEMT monolithic SPDT switch. Insertion mode bias: V_1 = 0 V, V_2 = -9 V. Isolation mode bias: V_1 = -9 V, V_2 = 0 V.

Small-signal performance of the fabricated AlGaN/GaN HEMT switch has been characterized on-wafer by HP8510C vector network analyzer through air-coplanar probes. Comparison of measured and simulated insertion loss and isolation is presented in figure 3. This figure shows that while measured isolation is reasonably close to the simulated one, considerable difference is observed in the insertion loss ($\approx$ 0.3 dB). The cause for this performance degradation has been determined by separate biasing of each of the four transistors in the circuit, which revealed that the transistor Q_3 does not have very hard pinch-off due to a fabrication problem. As a result, some portion of the input signal at $IN1$ port leaks to ground through the not-completely pinched-off $Q3$ instead of propagating to COM port through the open $Q1$. Measured return loss in the insertion mode is at least 13dB for frequencies up to 3GHz.

Results of single-tone power measurements at 2 GHz on the monolithic switch in the insertion mode are presented in figure 4. The data shows that the switch exhibits linear output power (P_{1dB}) equal to 30.2 dBm and the third harmonic input intercept point of approximately 46 dBm. The measured linear output power correlates very well with the prediction based on a simple I-V model in equation 3.

Output power and isolation as functions of input power in

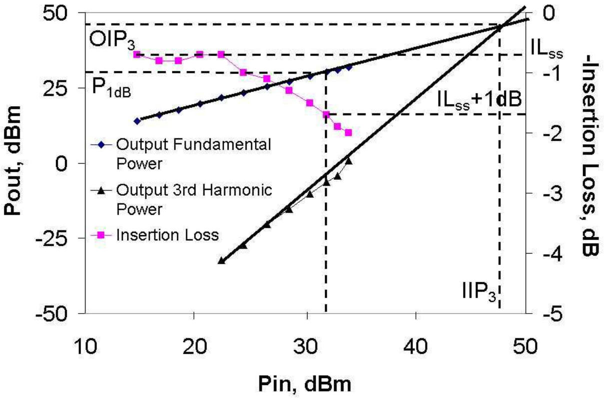

Fig. 4. Single-tone large-signal performance of the AlGaN/GaN HEMT MMIC SPDT switch in the insertion mode. V_1 = 0 V, V_2 = -9 V.

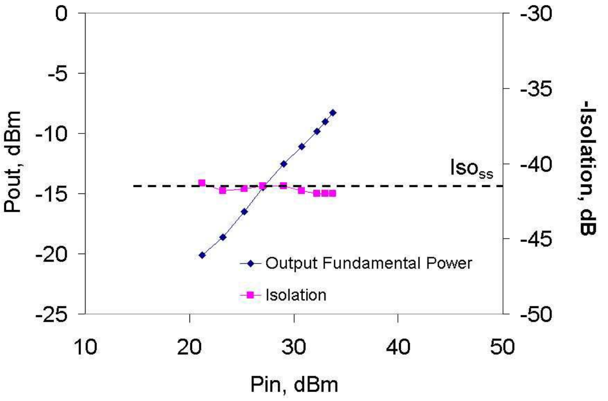

Fig. 5. Single-tone large-signal performance of the AlGaN/GaN HEMT MMIC SPDT switch in the isolation mode.V_1 = -9 V, V_2 = 0 V.

the isolation mode are depicted in figure 5. The switch has not demonstrated any deterioration in the isolation for input power levels up to more than 2 Watts. This result confirms the prediction that power handling of a GaN-based switch is limited more by the open-channel current than the breakdown voltage.

IV. SPDT SWITCH AS A VOLTAGE VARIABLE ATTENUATOR

The demonstrated SPDT switch can also be used as an analog voltage variable attenuator (VVA) or a digital attenuator. By changing two control voltages V_1 and V_2 the insertion loss of the circuit can be modulated continuously by almost 40 dB, the difference between the insertion loss and the isolation of the switch. Operation of the AlGaN/GaN HEMT switch as an analog VVA is depicted in figure 6.

Performance of the switch as a digital attenuator is summarized in table I.

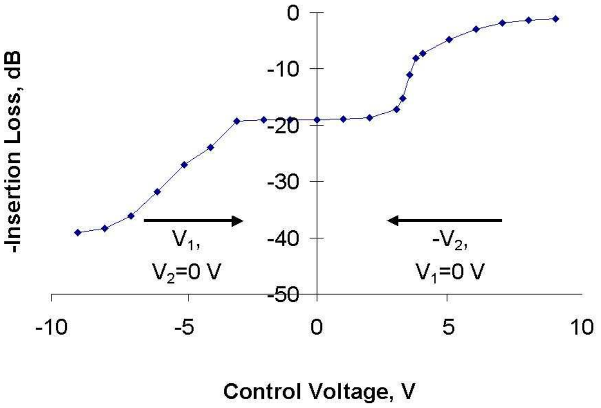

Fig. 6. Analog VVA based on the AlGaN/GaN HEMT SPDT switch at 3 GHz.

TABLE I

INSERTION LOSS AT 3 GHZ AS FUNCTION OF CONTROL VOLTAGES IN THE DIGITAL ATTENUATOR BASED ON ALGAN/GAN HEMT SPDT SWITCH.

Control Voltage	Insertion Loss, dB
V_1 = 0 V, V_2 = -9 V	1.1
V_1 = 0 V, V_2 = 0 V	19
V_1 = -9 V, V_2 = 0 V	39.1

V. CONCLUSION

Monolithic implementation of AlGaN/GaN HEMT - based SPDT switch has been demonstrated. The measured switch performance can be considered a good mix of reasonably low insertion loss, high isolation, high power handling capability and high linearity. Use of the SPDT switch as analog and digital voltage variable attenuators has also been demonstrated. High-power capability in conjunction with potentially high ESD thresholds, should make AlGaN/GaN HEMT an attractive option for various control applications.

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