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A New Design Approach of High Efficiency S-band 25 W Mixerless Power Modulator based on High Voltage 50V GaN-HEMT Technology

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Abstract- **In this paper, a novel concept for efficient and wideband, S band - 25W power modulator designed by taking the advantages of high voltage (50V) GaN HEMT technology is reported. The main objective of this study is to demonstrate the interest of merging both amplitude modulation and power amplification functions without the use of mixer in order to get high efficiency performances (>45%). To fully validate this principle, a two-stage power modulator circuit has been fabricated and tested. It delivers an output modulated (AM) power wave to a 50 Ω load and is based on a variable gain control principle with switched saturated states operating always at maximum Power Added Efficiency (PAE). PAE of around 45 % over 400 MHz RF bandwidth is achieved. With a fixed input power (CW) of 19 dBm, >10 dB output power range is obtained corresponding to 15V to 45V drain bias control, with 2.5 W and 25 W RF output powers respectively.**

Index terms: power modulator, GaN HEMT technology, variable gain control, switched saturated states, Power Added Efficiency.

I. INTRODUCTION

Modern wireless telecommunication systems has led to the increase in requirements for cost-effective, reliable and portable equipments for transmission. The efficient transmission of RF signals for communication purposes is undertaken by RF Power Amplifiers (RFPA's) which realizes the energy conversion from the DC supply to usable RF energy which is propagated in the free space. The power consumption of RF transmitter is thus governed by the power consumption of the power amplifier which demands the designers to come up with a solution to minimize the energy consumption thereby increasing the efficiency leading to a longer battery life.

The design criteria for RFPA requires addressing of the efficiency and linearity antagonism. The complex modulation schemes like n-QAM although improves the overall spectral efficiency but also leads to an increase in the peak to average power ratio (PAPR>10 dB) due to the non-constant envelope of such complex signals. This effect leads to the operation of the amplifier at back-off levels below saturation to ensure signal integrity (linearity) and by doing so the efficiency is degraded considerably. This implies that the PA must be designed for high PAPR implementing techniques for providing efficient operation at average power levels [1]. Several techniques have been implemented over the past few decades to efficiently amplify high PAPR signals such as Doherty [2], Envelope Elimination and Restoration (EER) [3] and Envelope Tracking [4] to improve the efficiency at back-off levels.

In this paper, we propose a power modulator design approach which converts digital baseband signal into analog RF power modulated signal at the output (RF Powers DACs). To focus on this target, we describe the preliminary 2-stage power modulator to validate the design methodology. This approach is based on a saturated variable gain (SVG) control which always operates at maximum PAE at each bias level and is done by taking the advantages of wide bandgap GaN HEMT technology which has proved to be a suitable candidate in high power microwave applications because of wide bandgap, high electron density and good thermal conductivity [5].

The design methodology in this paper addresses the deep class-B operation of GaN-HEMT devices and power gain control using supply modulation technique applied at drain port for both stages, driver stage ***(Cree 6W)*** and the power stage ***(Cree 25 W)*** respectively at a central frequency f_0 of 2.2 GHz. The driver stage, operating at a constant input power provides the input power variation required for the power stage which is coupled via inter-stage matching circuit (ISMC). Amplitude modulation and efficient DC to RF energy conversion will be implemented within the same module in near future using high speed switching GaN cells [6] in order to generate modulated RF power waves with high peak-to-average power ratios (PAPR>10 dB) with a large dynamic range in terms of gain and output power. Although the design of variable gain amplifiers (VGA) for linearization purposes [7] have been reported in literature in the past, but to our knowledge, power modulator with variable gain capabilities operating always at peak efficiencies has not been reported so far. The resulting system offers other advantages in terms of compactness and minimized losses as compared to conventionally existing systems.

The paper is organized as follows. In section II, the principle of the proposed power modulator and design methodology is presented. To validate the methodology imagined, in this paper, quasi-static measurement results of

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the fabricated device in section III with a special attention in demonstrating the high dynamic range at saturation in terms of gain and output power corresponding to different supply voltages at the drain terminal for both the driver and the power stage is presented.

II. POWER MODULATOR CIRCUIT DESIGN

A. Proposed Architecture

The conventional system and the proposed design of the power modulator is shown in fig.1 (a) and (b). It has to be noted that both the driver and power stage are supplied with a same discrete 4-level drain bias (15V, 25V, 35V and 45V). The driver stage provides an output power variation ($\Delta P_{Interstage}$) of around 4-6 dB to drive the power stage which in turn generates 4 discrete power levels P1-P4 corresponding to the supply voltage levels (15<Vdso<45) with large dynamic range in terms of output power and gain as illustrated in fig.2 (a) and (b). Fig.2 (a) shows the transfer of power from driver stage to the power stage (points A and B) where a constant input power applied to the driver stage generates the output power variation of the order of 4-6 dB ($\Delta P_{interstage}$) which provides the input power variations for the power stage leading to a large variation in output power (>10 dB) across the load (points C and D whereas fig.2 (b) shows the large variation of gain from the driver stage to the power.

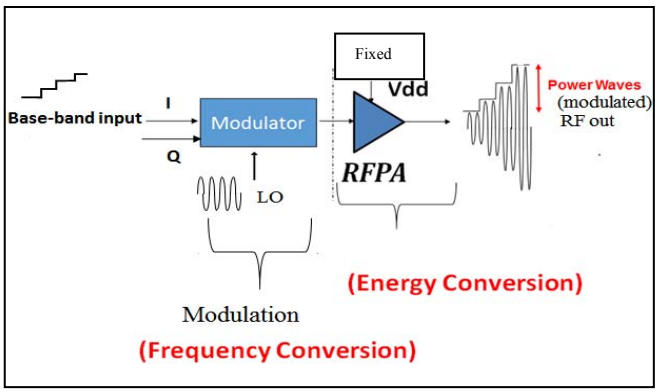

Fig.1 (a). Conventional approach (modulation and amplification are done separately)

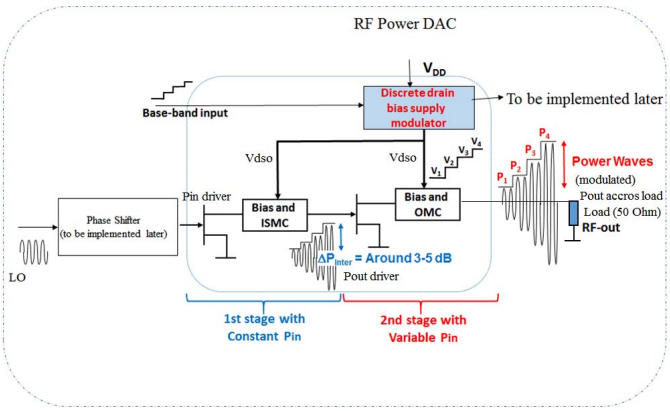

Fig.1 (b). Proposed Approach (Merging of both the functions together)

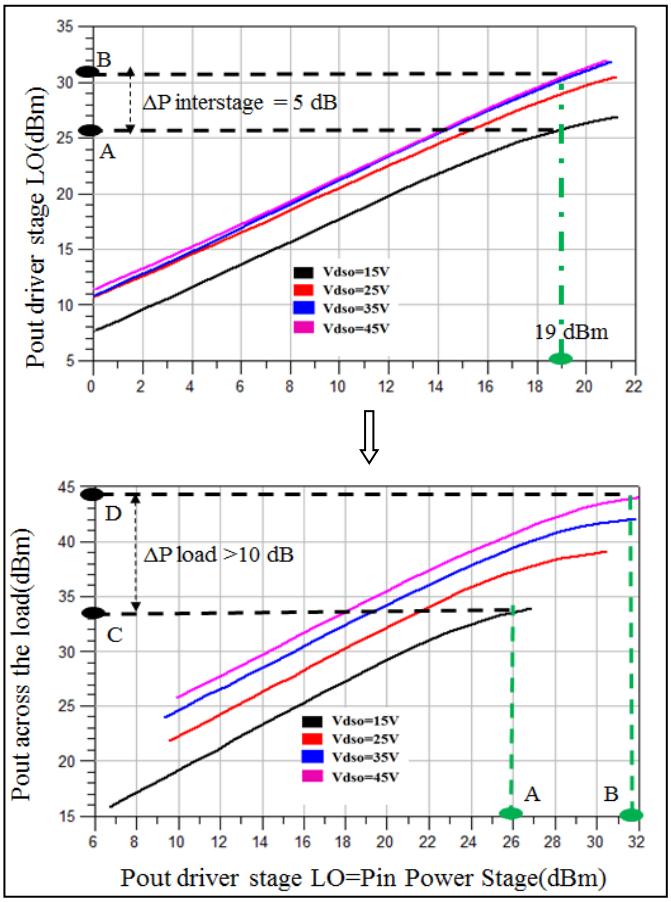

Fig.2 (a) Demonstration of power modulation principle (ADS simulated)

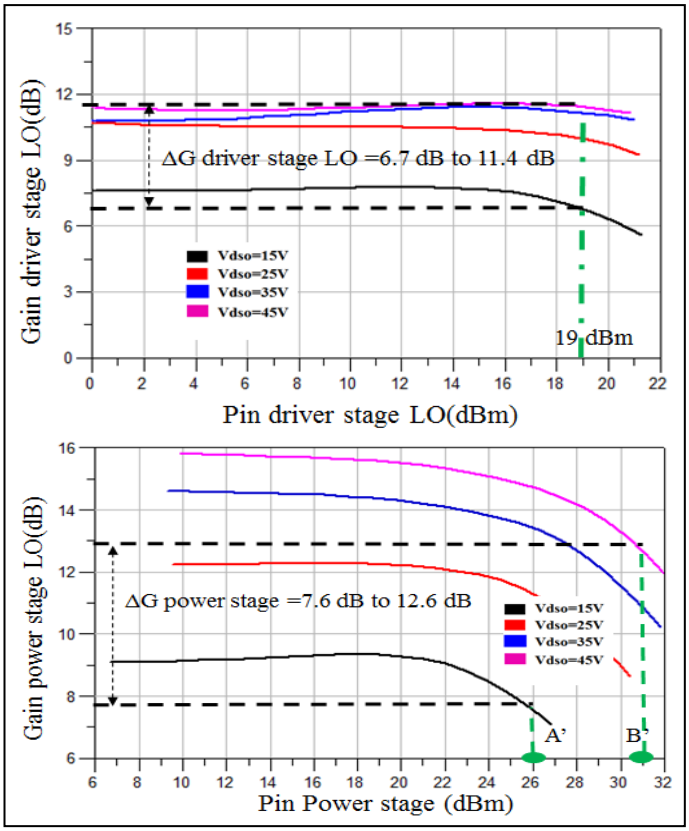

Fig.2 (b). Demonstration of gain variation principle (ADS simulated)

B. Design Methodology and Circuit Implementation

Harmonic balance simulations have been carried out using non-linear models of the transistors provided by Cree. Simulated load pull contours at fundamental and second harmonics were achieved for individual stages in order to target maximum PAE performances. The load impedance of the driver stage is power matched (complex conjugate) to the input impedance of the power stage with the help of an inter-stage matching circuit (ISMC). Finally, the driver and the power stage was similarly biased with four voltage levels at their drain ports and a constant CW input power carrier for the driver determined by simulation for maximum PAE was applied. Gate bias voltages for both the stages were fixed to -2.8 V near the pinch-off point. Fig.3 shows the final fabricated device. Linear and non-linear stability at the gate bias circuit over the bias range has been obtained without using any capacitors and hence stability is obtained without impacting the envelope bandwidth at the drain axis of the overall circuit. The proposed device is implemented on Rogers 4350 substrate with ε_r=3.48 and thickness of 0.508 mm. The principle objective was to verify the methodology of possibility of modulation in terms of dynamic range with respect to gain and output power with supply modulation technique using measurements which will be later used to combine with a specially designed supply modulator in XLIM laboratory [6] to come up with a less complex, efficient and a compact system that can mix the objectives of energy conversion and AM modulation together without actually using a mixer as in conventional AM modulated systems. It is also foreseen to use phase shifter at the input of the driver stage to implement phase modulation and achieve QAM modulation schemes.

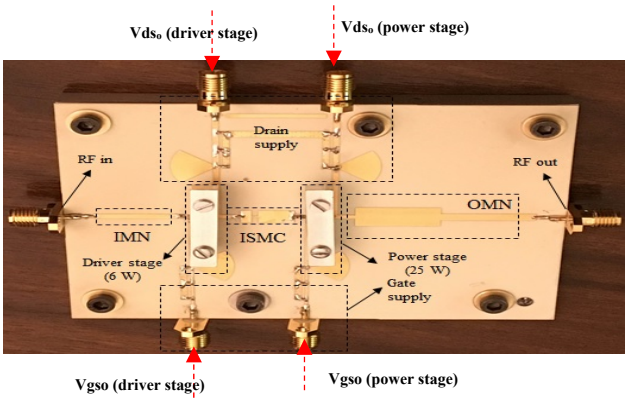

Figure 3. Fabricated two-stage GaN-HEMT power modulator (9cm x 7cm)

III. EXPERIMENTAL RESULTS

We implemented the two-stage circuit using Cree GaN-HEMT's ***CGHV1F006S*** for the driver stage and ***CGHV1F025S*** for the power stage respectively and investigated the overall performances in terms of efficiency, output power and gain for each drain bias voltage at a constant input power of 19 dBm.

The measured input return loss acceptable (<-10 dB) over a bandwidth of around 400 MHz from 2 to 2.4 GHz for both the minimum and maximum values of the drain supply whereas the measured output return loss is <-10 dB for around the same bandwidth range whereas the measured small signal gain varies from 16 dB (15V) to 28 dB (45V) respectively.

Fig.4 depicts the measured overall system output power as a function of driver stage input power in dBm at 2.2 GHz. At a constant input power of 19 dBm, the output powers corresponding to Vds_o values of 15V and 45V are around 33 dBm and 44 dBm respectively with a dynamic range of around 11 dB in terms of output power giving an indication for a power modulation.

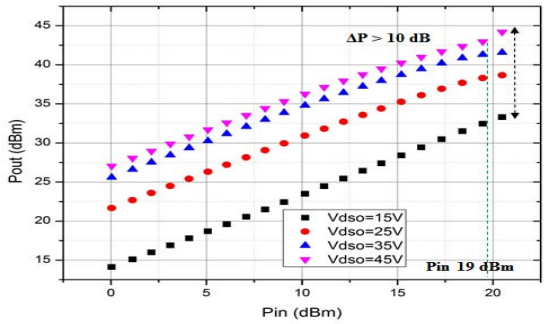

Figure 4. Pout (overall system) vs. Pin (driver stage LO)

Fig.5 shows the measured overall system PAE as a function of driver stage input power in dBm at 2.2 GHz. Proposed design provides a measured PAE of around 50% at 45V and 37% at 15V respectively at a constant input power and at saturation.

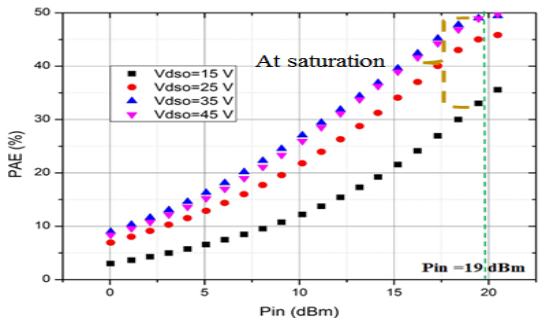

Figure 5. PAE (overall system) vs. Pin (driver stage LO)

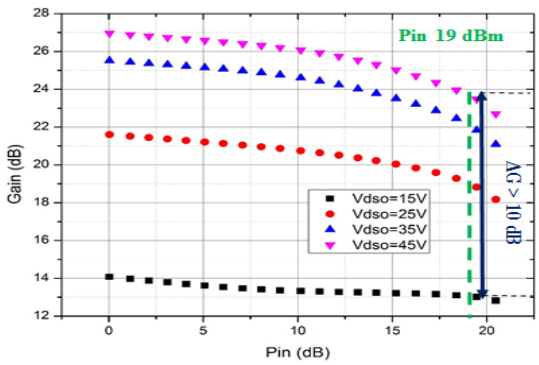

Figure 6. Gain (overall system) vs. Pin (driver stage LO)

Fig.6 shows the measured gain as a function of input power in dBm at 2.2 GHz for 15V<Vds_o<45V. Gain variations of >10 dB from 13 dB to 24 dB is obtained in the measurements at saturation at a fixed input power indicating the validity of the methodology imagined for possible feasibility of modulation and the saturated states indicating the efficient energy conversion from DC to RF. To demonstrate the wideband capabilities of such a system, the measurements were repeated at different frequencies within the bandwidth of interest (2-2.4 GHz) and the overall power characteristics as a function of frequency is shown in fig.7. and fig.8.

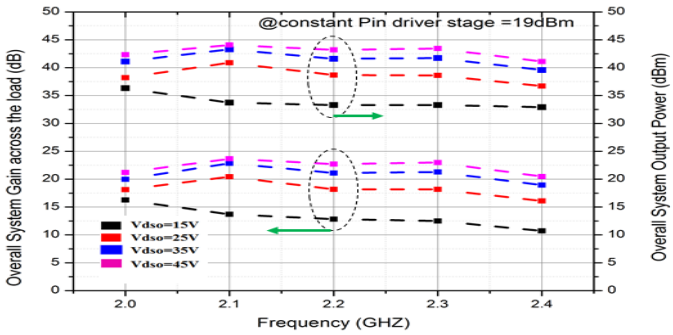

Figure 7. Overall system Pout and Gain vs. Frequency

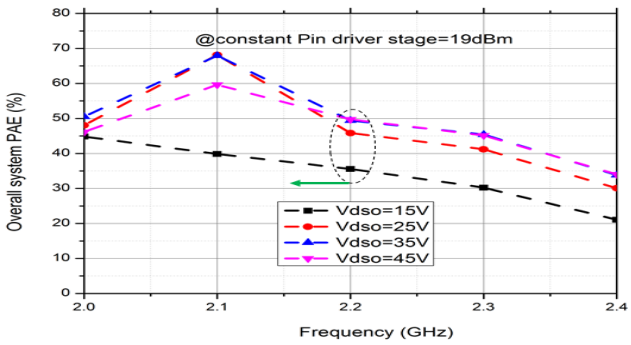

Figure 8. Overall system PAE vs. Frequency

Finally, to validate the modulation function, fig.9 highlights the measured overall system gain and phase variations along with saturated PAE performances vs supply voltage Vdso.

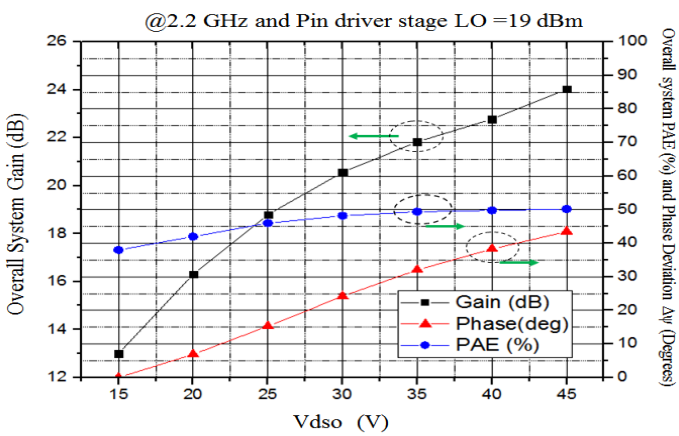

Figure 9. Overall system Gain, Δψ and PAE vs. Vdso

CONCLUSIONS

We have demonstrated and validated the preliminary step towards development of a wideband two-stage power modulator with power gain and output power variations of over 10 dB always operating at or very near to maximum PAE using the principle of supply modulation which has never been reported previously in literature. In this study, a mixerless power modulator design has been proposed, which can be seen as an RF power generation device based on bias controlled saturated variable gain (SVG).

The proposed high efficiency power modulator concept is inspired from EER technique. Originality stands in a specific two stage architecture with a common drain bias supply variation. Further work is being under development to integrate GaN switching cells for discrete supply modulation. The device can be combined with an analog phase shifter to achieve phase shift capabilities. This SVG building block can find great interest in application to reconfigurable phased array antennas with enhanced power efficiency. A specific set-up bench is being developed in our lab to manage both the baseband signals and the RF carrier in order to further validate the built-in demonstrator in near future.

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