Reliability and Efficiency Aspects of Harmonic-Control Amplifiers

Bernhard Ingruber, *Member, IEEE*

***Abstract*—Reverse gate current flowing through a power device of a harmonic control microwave amplifier reduces its power-added efficiency (PAE) and its reliability. This study reports on theoretical analysis and measurement results of the breakdown behavior of a GaAs MESFET at class F and half sinusoidally driven harmonic control amplifier (hHCA) operation. In a class F amplifier reverse gate current is observed in power saturation and PAE decreases with increasing drain supply voltage. On the other hand, in an hHCA any reverse gate stress is avoided due to the reduction of input voltage swing. This improves not only PAE, but also reliability.**

***Index Terms*— Class F, gate current, harmonic control, high efficiency, power amplifier, reliability.**

I. Introduction

FOR a well-constructed high-efficiency microwave power amplifier, power saturation is a combined effect of forward gate conduction and drain-to-gate breakdown [1]–[4]. But as the former has only a small influence on power-added efficiency (PAE), the latter reduces PAE due to the appearance of a drain current component which is in phase with the drain voltage and, therefore, causes additional power dissipation in the transistor [1], [2], [4], [5]. Reliability tests on GaAs MESFET's under dc and radio frequency (RF) excitation at elevated temperatures have shown gradual degradation of output power over stress time due to drain-to-gate breakdown voltage (V_{BD}) degradation at reverse gate currents, which finally resulted in catastrophic failures [6]–[9]. On the other hand, such tests indicated that forward gate currents of the same magnitude have only a small influence on the forward Schottky characteristic [7] and no catastrophic failures occurred even at two times the test duration, where all devices stressed with reverse gate current failed [8]. It is known from the literature that most failures of power devices under RF operation occur under avalanche breakdown at reverse gate currents [6]–[10].

II. Amplifier Theory

In a harmonic control amplifier (HCA) PAE is optimized by terminating fundamental and harmonic frequencies at its output and input. The most common HCA is the class F amplifier, which is biased at its input at class B and harmonics are controlled such that drain voltage becomes rectangular and drain current half sinusoidal. In Fig. 1 input and output characteristics of an idealized field-effect transistor (FET) and the corresponding gate and drain wave forms and dynamic load line at class F operation are indicated. When the sinusoidal input voltage is increased, two things happen. First, the positive gate voltage swing drives the device into forward conduction, which means that positive gate current flows through the gate–source diode and the drain current saturates at the maximum current level (I_m). The drain voltage remains unchanged. Secondly, the negative gate voltage swing causes drain-to-gate breakdown followed by reverse current through the gate–drain diode. Consequently, drain current flows within the second half of the time period. Again, the drain voltage remains more or less unchanged. It is important to note that both, forward conduction and reverse breakdown, increase the mean value of drain current and, therefore, increase output power. But as the device remains turned off in the second half of the time period at forward conduction only, PAE is unchanged only at this condition, whereas at reverse breakdown PAE is reduced with rising reverse current due to the rise of power dissipation in the device. Therefore, the avoidance of reverse breakdown is not only important from reliability point of view but also to maximize PAE.

For this class F amplifier the upper limit of drain-to-source voltage $(V_{DS\max})$, where drain-to-gate breakdown (V_{BD}) occurs, is

$$V_{DS\max,F} = V_{BD} + 2 \cdot V_p - V_f \tag{1}$$

where the pinchoff voltage (V_p) is negative and V_f is the forward turn-on voltage of the gate diode. The resulting maximum drain supply voltage (V_{DD}) can be calculated to be

$$V_{DD,F} = \frac{V_{DS\max,F} + V_K}{2} = \frac{V_{BD} + 2 \cdot V_p - V_f + V_K}{2}. \tag{2}$$

V_K is the knee voltage.

Recently, we reported on the half sinusoidally driven harmonic control amplifier (hHCA) concept [11], where a half sinusoidal input signal drives an amplifier with class F output matching (Fig. 2). As compared with class F the reduced input voltage swing of the hHCA not only improves power gain up to 6 dB and, therefore, PAE, but also $V_{DS\max}$ is increased by $|V_p| + V_f$ to

$$V_{DS\max,hHCA} = V_{BD} + V_p \tag{3}$$

and V_{DD} to

$$V_{DD,hHCA} = \frac{V_{BD} + V_p + V_K}{2}. \tag{4}$$

Manuscript received June 23, 1999; revised August 16, 1999.

The author is with the Technische Universität Wien, Institut für Elektrische Mess- und Schaltungstechnik, A-1040 Vienna, Austria.

Publisher Item Identifier S 1051-8207(99)09813-X.

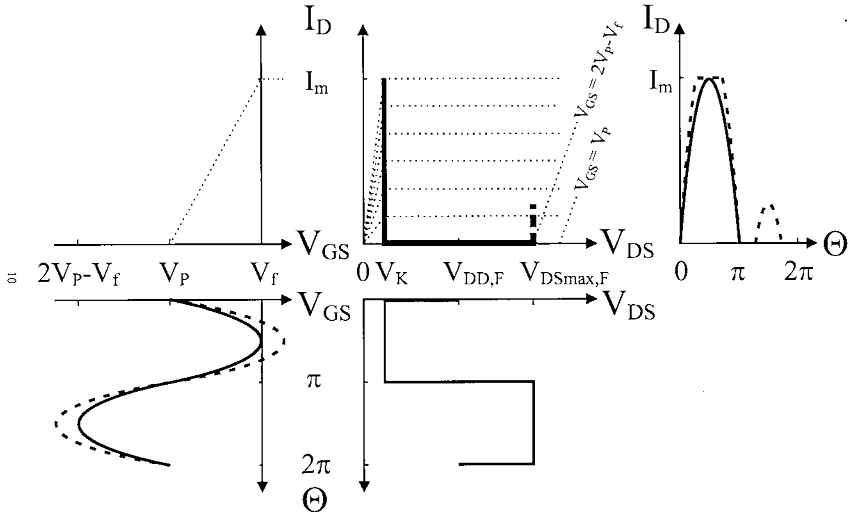

Fig. 1. Input and output characteristics of an idealized FET, dynamic load line, gate voltage, drain voltage, and drain current wave forms at class F operation at maximum drain supply voltage $V_{DD,F}$ below output power saturation (—) and in saturation (- - - -).

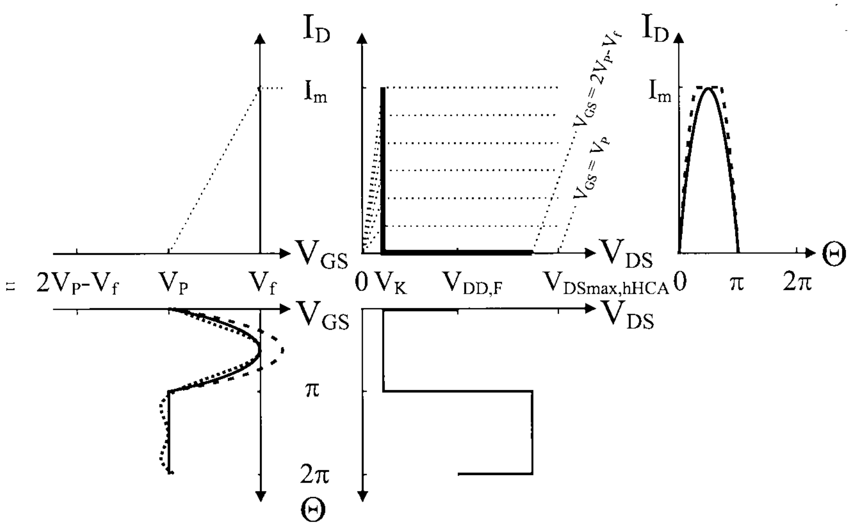

Fig. 2. Input and output characteristics of an idealized FET, dynamic load line, gate voltage, drain voltage, and drain current wave forms at hHCA operation at the same drain supply voltage as for class F operation below output power saturation (—) and in saturation (- - - -). In practice, the half sine can be approximated by the fundamental frequency along with the right portion of second harmonic $(\cdots\cdots)$.

This higher drain supply voltage finally results in an increased output power capability.

At a drain supply voltage equal to $V_{DD,F}$ forward conduction at power saturation is predominating for the hHCA concept and reverse breakdown is avoided (Fig. 2), whereas for class F both effects are observed (Fig. 1). Consequently, PAE and reliability of the hHCA at given output power level are improved.

III. Measurement Results and Discussion

Our practical realization of an L-band hHCA consists of a commercially available power GaAs MESFET and distributed matching networks at its input and output up to the third harmonic frequency. The half sinusoidal input signal is sufficiently approximated by the fundamental frequency along with the right portion of second harmonic (Fig. 2). These signal components, which are fed through two uncoupled ports into the power amplifier, are generated by a resistively loaded class B driver amplifier. For class F operation, the second harmonic input port of the power amplifier is terminated by a sliding short which is adjusted for maximum PAE operation.

Fig. 3 illustrates measured PAE and gate current (I_G) of the class F amplifier as a function of input power at three different drain supply voltages ($V_{DD} = 6.6$ V, 7.4 V, 7.8 V). Below saturation, gate current is zero for all drain supply voltages and the differences in PAE at a given input power level result from suboptimum drain wave forms at higher drain supply voltages. As expected from theory, power saturation is a combined effect of forward conduction and reverse breakdown. Maximum PAE is obtained at $V_{DD} = 6.6$ V, where only small reverse gate current is observed. At higher drain supply voltage reverse gate current is much more pronounced. Finally, forward conduction dominates the gate current in deep saturation. Here, drain

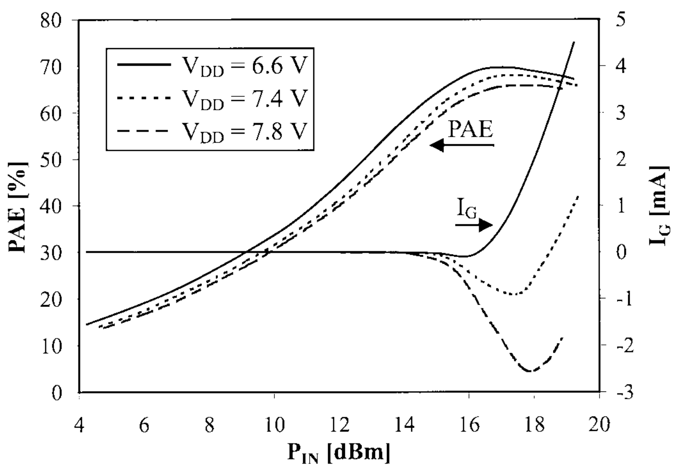

Fig. 3. Measured PAE and gate current (I_G) versus input power of a class F amplifier at different supply voltages (V_{DD}).

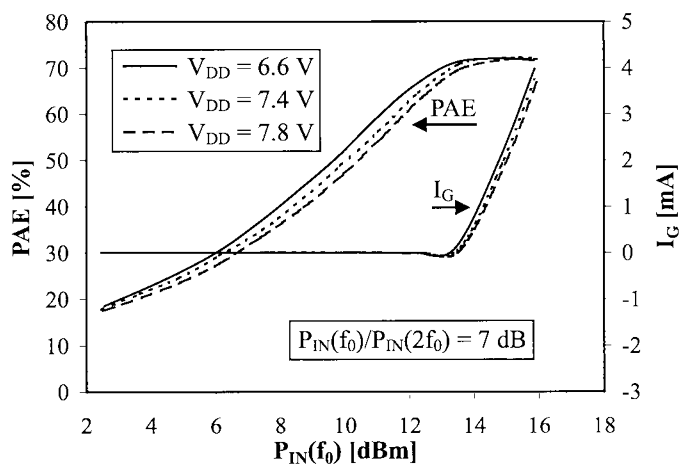

Fig. 4. Measured PAE and gate current (I_G) versus fundamental frequency input power of an hHCA at different supply voltages (V_{DD}).

voltage wave forms are optimum for all supply voltages and, as explained above, the differences in PAE result from drain current components which are in phase with the drain voltage.

PAE and I_G versus fundamental frequency input power measured at the hHCA are shown in Fig. 4 for the same drain supply voltages as for the class F amplifier. For a fair comparison fundamental frequency to second harmonic input power ratio are held constant to the optimum value of 7 dB and the gate bias voltage is changed accordingly to the input signal to achieve equal positive half-wave input signal, which is indicated by the mean value of the drain current. Here, only small reverse gate currents are observed and the overall gate current is dominated by forward current which starts at output power saturation. Again, the differences in PAE below saturation result from suboptimum drain wave forms at higher drain supply voltages. But due to the avoidance of reverse gate current, there are no differences in PAE in deep saturation at all drain supply conditions.

At equal drain supply voltage power gain of the hHCA is about 3 dB larger than of the class F amplifier. This further improves PAE. An inspection of the gate current slopes of Fig. 3 and Fig. 4 indicates that they are comparable at $V_{DD,F} = 6.6$ V at class F and $V_{DD,hHCA} = 7.8$ V at hHCA operation. As the device has a pinchoff voltage of $V_p = -4.3$ V, a knee voltage of $V_K = 1$ V, and a turn-on voltage of $V_f = 1$ V, the difference between the drain supply voltages of both amplifier concepts calculated from (2) and (4) should be 2.65 V. One reason for this deviation of the simplified theory from the measurement results is that the half sinusoidal input signal, which is approximated by fundamental frequency and second harmonic only, has slight overshoots in the second half of the time period (Fig. 2). Therefore, the gate bias voltage has to be selected more negative to guarantee the switching-off of the device within this time period, which reduces the margin of safety for drain-to-gate breakdown [see (3)]. On the other hand, the simplified theory does not consider the bias dependence of the input impedance which, of course, influences the resulting input voltages. Nevertheless, a concept dependent increase of 1.2 V of drain supply voltage is marked and results in an increase of 1.4 dB of saturation output power for this realization.

IV. Conclusions

The hHCA concept is an efficient way to improve reliability of the device of a microwave power amplifier. Due to the reduction of input voltage swing any reverse current stress is avoided, which increases PAE and output power capability, too.

References

[1] T. A. Winslow and R. J. Trew, "An investigation of efficiency limiting mechanisms in GaAs MESFET amplifiers," in *Proc. 22nd European Microwave Conf.*, 1992, pp. 1195–1200.
[2] S. H. Wemple, W. C. Niehaus, H. M. Cox, J. V. Dilorenzo, and W. O. Schlosser, "Control of gate-drain avalanche in GaAs MESFET's," *IEEE Trans. Electron Devices*, vol. 27, pp. 1013–1018, June 1980.
[3] W. R. Frensley, "Power-limiting breakdown effects in GaAs MESFET's," *IEEE Trans. Electron Devices*, vol. 28, pp. 962–970, Aug. 1981.
[4] T. A. Winslow and R. J. Trew, "Principles of large-signal MESFET operation," *IEEE Trans. Microwave Theory Tech.*, vol. 42, pp. 935–942, June 1994.
[5] T. Sonoda, S. Sakamoto, N. Kasai, M. Yamanouchi, S. Takamiya, and Y. Kashimoto, "High-efficiency and high reliable 20 W GaAs power field-effect transistor in C band," *Jpn. J. Appl. Phys.*, vol. 31, pp. 2374–2381, Aug. 1992.
[6] H. Hasegawa, K. Katsukawa, T. Itoh, T. Noguchi, and Y. Kaneko, "High reliability power GaAs MESFET under RF overdrive condition," in *IEEE MTT-S Int. Microwave Symp. Dig.*, Atlanta, GA, 1993, pp. 289–292.
[7] S. Kashiwagi, S. Takase, T. Usui, and T. Ohono, "Reliability of high frequency high power GaAs MESFET's," in *Proc. 25th Annu. Int. Reliability Pysics Symp.*, New York, NY, 1987, pp. 97–101.
[8] K. J. Russel and J. K. Dhiman, "Power GaAs FET RF life test using temperature-compensated electrical stressing," in *Proc. 24th Annu. Int. Reliability Pysics Symp.*, New York, NY, 1986, pp. 150–156.
[9] K. A. Chistianson, J. A. Roussos, and W. T. Anderson, "Accelerated life testing and failure analysis of single stage MMIC amplifiers," *IEEE Trans. Electron Devices*, vol. 41, pp. 1435–1443, Aug. 1994.
[10] J. L. B. Walker, *High-Power GaAs FET Amplifiers*. Boston, MA: Artech House, 1993.
[11] B. Ingruber, W. Pritzl, D. Smely, M. Wachutka, and G. Magerl, "High-efficiency harmonic-control amplifier," *IEEE Trans. Microwave Theory Tech.*, vol. 46, pp. 857–862, June 1998.