EFFECT OF INPUT HARMONIC TERMINATIONS ON HIGH EFFICIENCY CLASS-B AND CLASS-F OPERATION OF PHEMT DEVICES.

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Abstract

Device level harmonic balance simulations are used to show that very high efficiency can be achieved in PHEMT Class-B and Class-F amplifiers if efforts are made to provide proper input as well as output harmonic terminations. The simulations use a gate capacitance model which accurately describes the C_{gs} versus V_{gs} dependence for the PHEMT and are illustrated with waveform and dynamic loadline plots which relate directly to the idealized textbook view of high efficiency operation.

Introduction

Textbook explanations [1,2] of FET power amplifier operation typically assume that the input signal driving the device current generator is a pure sinusoid. High efficiency operation in class-B or class-F [1] modes, with the device biased near pinch-off, is achieved by properly terminating harmonics at the output of the current generator. The resultant output waveforms, for an ideal generator, are a half-wave rectified current, and voltages which are sinusoidal or square-wave for class-B and class-F respectively. This idealized picture is significantly altered in a real MESFET or PHEMT device, not only because of the non-ideal current generator, but also because the input capacitance C_{gs} is voltage dependent. The non-linear varactor-like effect of C_{gs} distorts the input waveform thus destroying the *a priori* assumption of sinusoidal drive. A possible solution to any performance limitation introduced by this effect is to retrieve the sinusoidal drive by application of short circuit input harmonic terminations, ideally placed directly across C_{gs}.

Application of input harmonic tuning to MESFETs is expected to produce only modest improvements in efficiency because of the relatively benign dependence of C_{gs} on V_{gs} for this device. Various reports citing both simulated and experimental results tend to confirm this assertion [3-5]. The PHEMT device in contrast shows a very steep gradient in its C_{gs} versus V_{gs} dependence, thus much greater improvements in efficiency are expected.

In this paper the effect of input harmonic terminations on power PHEMT performance is demonstrated by device-level harmonic balance simulations using a real device large signal model which accurately reproduces the terminal voltage dependence of the gate capacitance. It is shown that power added efficiency at the chosen simulation frequency of 5.0 GHz is dramatically improved in both class-B and class-F operation by application of ideal input harmonic short circuits. Simple practical circuits, including a lumped capacitance placed at the input, have a similar effect on improving efficiency. The results are illustrated with waveform and dynamic loadline plots which relate directly to the idealized textbook representations.

Large Signal PHEMT Model and Device Level Simulation

Simulations were performed in HP/EEsof Libra 6.0 using the circuit shown schematically in Figure 1.

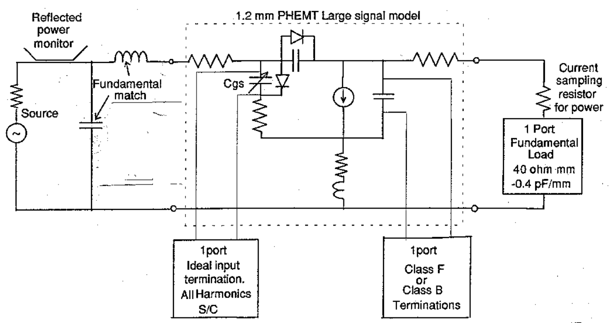


Fig.1 Schematic circuit for device level simulation of PHEMT

The PHEMT large signal model, pertaining to a 1.2 mm periphery 0.25 micron gate length production device, utilized the conventional equivalent circuit as shown in Fig.1 with standard Modified Materka current control and diode conduction equations. Gate capacitance C_{gs} as a function of its terminal voltage V_{gs} was modeled by the expression,

$$C_{gs} = \frac{\left(C_{gs0} - C_{dg}\right)}{2} \cdot \tanh\left(A_{cgs}\left(V_{gs} - V_{cgs}\right)\right) + \frac{\left(C_{gs0} + C_{dg}\right)}{2}$$

where C_{gs0}, A_{cgs} and V_{cgs} are fitting constants and C_{dg} is the gate-drain capacitance at the chosen quiescent bias point. In Figure 2 this expression is shown fitted to typical PHEMT data at Vds=7 obtained from small signal models extracted over a range of gate bias. The input is matched at the 5 GHz fundamental by a simple series L shunt C circuit tuned for best large signal return loss. The output fundamental load was chosen as 40 ohm mm in shunt with a capacitance of $-C_{ds}$ pF/mm and was conveniently realized as a simple 1-port s-parameter file[1]. An ideal class-B output termination, comprising shorts at all harmonics placed directly across the current generator, was realized by a simple four-line 1-port s-parameter file. This same element served as an ideal input harmonic termination placed across C_{gs}. Similarly a 1-port s-parameter file was constructed for ideal class-F output terminations comprised of short circuits at even harmonics and open circuits at odd harmonics [1].

[1] Choice of fundamental load was not critical to the conclusions of this investigation.

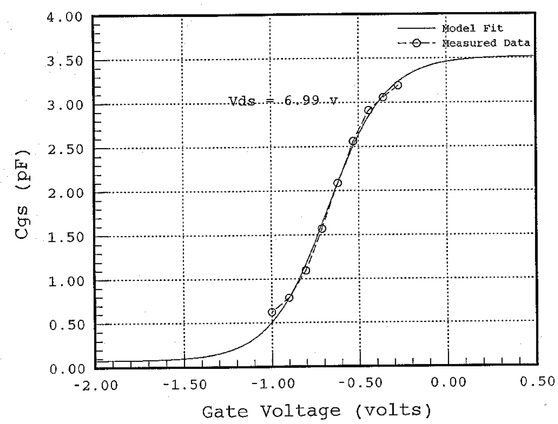


Fig 2. Example of C_{gs} model fitted to measured data for 1.2 mm PHEMT

Results

Simulation results shown here were obtained at V_{ds}=7 with the gate biased close to pinch-off at V_{gs}=-0.8. Figure 3 compares power and efficiency performance versus input power in class-F operation with and without input harmonic terminations. Peak efficiency is 81 % with input harmonic shorts but this drops dramatically to only 49 % when the terminations are removed, while power output is essentially unaltered.

The explanation is revealed clearly in Figures 5 and 6. These show the input voltage across C_{gs}, the output voltage at the current generator and the output current waveforms for operation near the peak efficiency point. Also shown are the dynamic loadlines plotted from the output waveforms. In Fig. 5, with input harmonic terminations present, the input voltage is a pure sinusoid and the output current approximates to a half-sinusoid rectified waveform. The output voltage approximates well the ideal square wave of class-F operation. The imperfections in these output waveforms are introduced mainly by the non-ideal I-V characteristics of the device. The overlap area, representing power dissipated within the device, is small hence the efficiency is high. The dynamic loadline shows the characteristic shape of class-F operation including the vertical portion near the voltage knee corresponding to the flat bottom of the voltage waveform.[2]

In Fig. 6, with input harmonic shorts absent, the input voltage waveform is severely distorted and the output current shows little resemblance to the ideal half-sinusoid. The output voltage is still squared-off but the area of the overlap region is much increased. This deterioration is reflected in the dynamic load-line which now resembles that for class-A operation. Figures 4, 7 and 8 show similar results for the case of class-B output terminations. Output voltages are now sinusoidal, because all harmonics are shorted, but the output current waveform changes from near half-wave, with input harmonics terminated, to near sine-wave with input harmonics un-terminated. The peak efficiencies are 70 % and 48 % respectively. These waveform differences are similarly reflected in the dynamic loadlines.

Finally, Figures 9 and 10 show the effect on class-F operation of input harmonic terminations provided by simple practical circuits. A series L,C network resonating the second harmonic placed at the device input gives a peak efficiency of 77 %. The dynamic loadline resembles that for the ideal termination. A broader band solution is simply to place a lumped capacitor at the device input. This element decreases the ease of broad in-band matching but is effective at improving efficiency. Figure 10 shows power and efficiency performance as a shunt capacitor at the input is increased in value from zero to 1.2 pF. The gain is reduced as the fundamental input match degrades but efficiency increases from 49 % to a peak of 71 %. This approach to providing input harmonic terminations was successfully used in a high efficiency C-band power MMIC amplifier which has been described previously [6]. Alternative proposed approaches to mitigating the effect of non-linear input capacitance include a novel compensation technique using an inverted diode [5].

Conclusions

It has been shown that optimum efficiency class-B and class-F operation of PHEMT power amplifiers requires attention to providing proper harmonic terminations at the input as well as the output of the device. Short circuit harmonic terminations at the input eliminate the distortion in the input voltage and resultant output current waveform which otherwise arises from the non-linear input capacitance of the device causing degraded efficiency. It was shown that power added efficiency of over 80% in class-F operation at C-band is predicted under these conditions thus realizing the full performance capabilities of the device. These conclusions were revealed by device-level harmonic balance simulations using a large signal model which includes an accurate formulation for the C_{gs} versus V_{gs} dependence in the PHEMT.

References

[1] H.L. Kraus, C.W. Bostian and F.H. Raab., "Solid State Radio Engineering", John Wiley & Son., 1980.

[2] John L.B. Walker, Editor., "High-Power GaAs FET Amplifiers", Artech House., 1993

[3] M. Maeda et. al., "Source Second Harmonic Control for High Efficiency Power Amplifiers", IEEE Trans. MTT , vol. 43 pp. 2952-2958, 1995

[4] S. Watanabe et. al., "Simulation and Experimental Results of Source Harmonic Tuning on Linearity of Power GaAs Under Class AB Operation" 1996 IEEE MTT-S Dig., pp. 1771-1774.

[5] K. Jeon et. al., "Input Harmonic control using non-linear capacitor in GaAs FET Power Amplifier", 1997 IEEE MTT-S Dig. pp. 817-820.

[6] P.M. White and T.M. O'Leary., "A 50 % Efficiency 8W C-Band PHEMT Power MMIC Amplifier." IEEE GaAs IC Symp. Digest, pp 277-280, 1995.

[2] The dynamic loadline moves outside the leading edge of the *extrinsic* I-V characteristics which are plotted by Libra. The dynamic loadline should correctly be overlaid on the *intrinsic* characteristics.

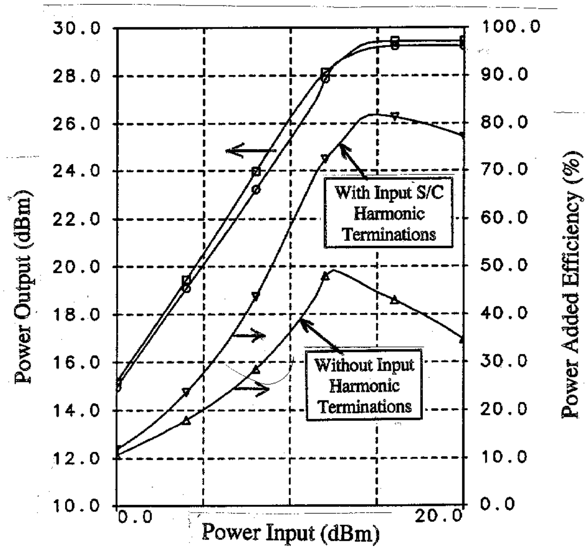


Fig 3. Performance of 1.2 mm PHEMT at 5 GHz with class-F output terminations comparing simulation with and without input harmonic terminations.

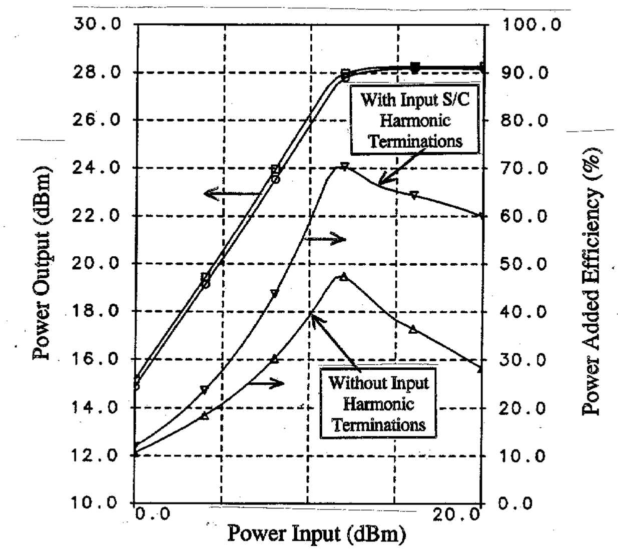


Fig 4. Performance of 1.2 mm PHEMT at 5 GHz with class-B output terminations comparing simulation with and without input harmonic terminations

Fig. 5. Waveforms and dynamic loadline for PHEMT with class-F output and **S/C input harmonic terminations.**

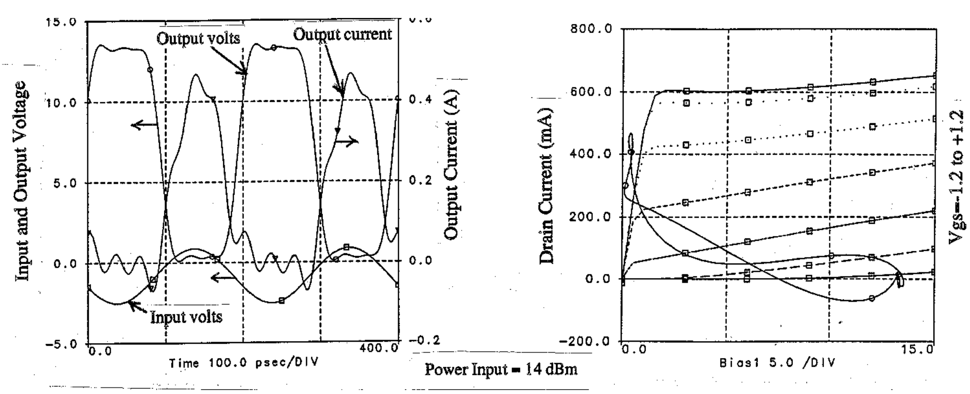


Fig. 6 Waveforms and dynamic loadline for PHEMT with class-F output and **no input harmonic terminations.**

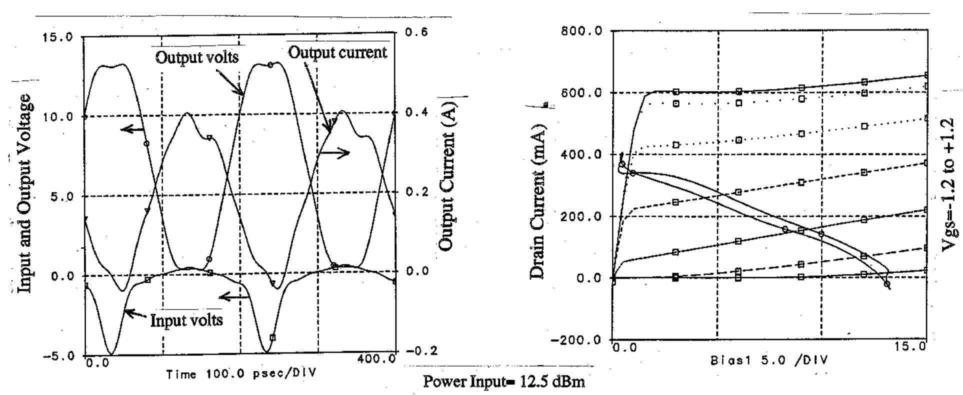


Fig 7 Waveforms and dynamic loadline for PHEMT with class-B output and **S/C input harmonic terminations**.

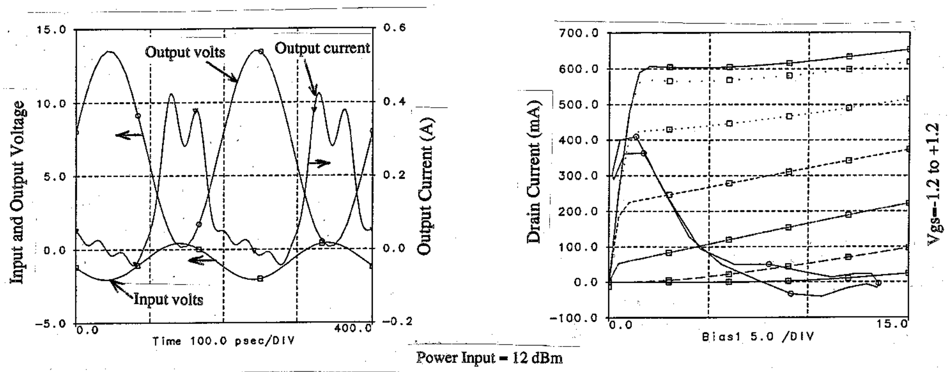


Fig 8 Waveforms and dynamic loadline for PHEMT with class-B output and **no input harmonic terminations.**

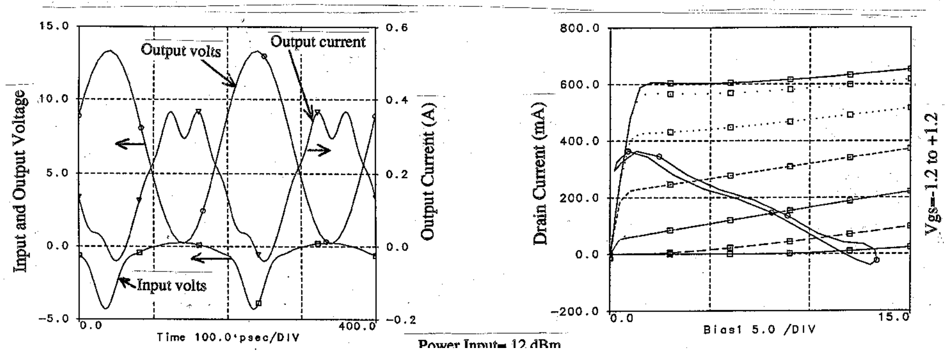
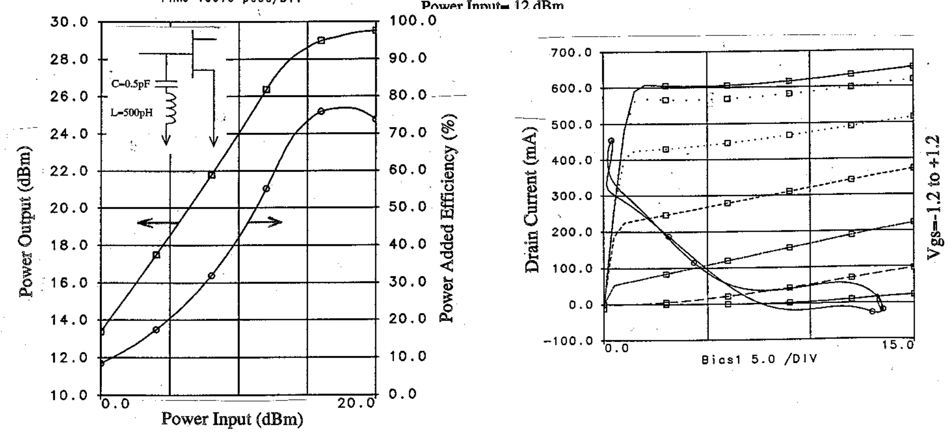
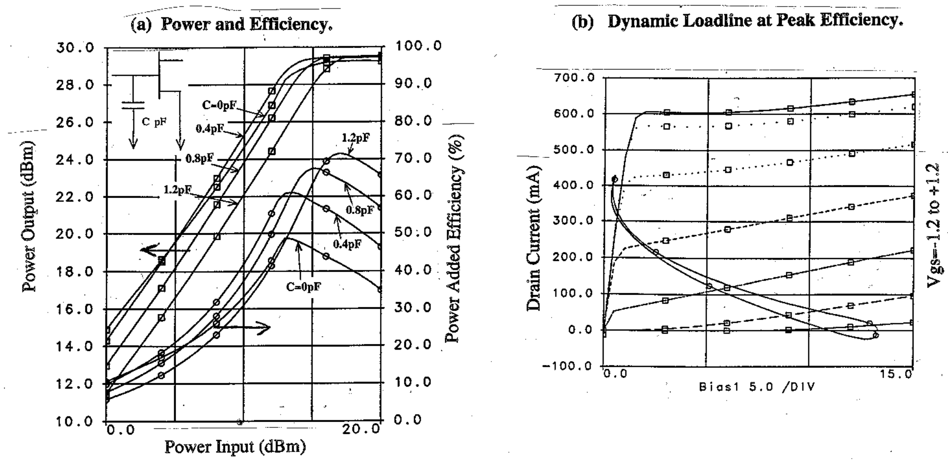


Fig 9 Performance of 1.2 mm PHEMT at 5 GHz with class-F output terminations and simple shunt L,C network providing an input short circuit at the second harmonic



(a) Power and Efficiency. **(b) Dynamic Loadline at Peak Efficiency.**

Fig. 10 Performance of 1.2 mm PHEMT at 5 GHz with class-F output terminations and input harmonic terminations provided by lumped capacitor.



(a) Power and Efficiency for Various Capacitor Values. **b) Dynamic Loadline at Peak Efficiency for C=1.2 pF.**