HARMONIC TUNING OF POWER FETs AT X-BAND

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ABSTRACT

We report on a study of high-efficiency, harmonic-tuned, class-B operation of power MESFETs at X-band. Hybrid, single-stage $1200\mu m$ power FET amplifiers were fabricated with the output circuit designed to provide optimum load impedance at the fundamental frequency (10 GHz) and short at the second harmonic. Power-added efficiency of 61% at an output power level of 450mW and 7dB power gain were obtained at 10GHz. The corresponding drain efficiency was 75%. The second harmonic level in the output was suppressed to less than -40 dBc level over a 4% frequency bandwidth. The improvement in the efficiency was at the expense of lower operating voltage and power density (0.4W/mm) when compared with class-A or class-AB amplifiers made from similar devices. Theoretical harmonic-balance analysis of these tuned class-B amplifiers were also performed and the results agree fairly well with the measured data.

INTRODUCTION

High-efficiency power amplifiers are crucial components of solid-state phased-array T/R modules. While GaAs power FET technology has progressed significantly over the past decade, high-efficiency (> 50%) operation of power FETs with more than 1 W output power level at X-band and beyond remain a challenge. There are two major factors limiting the efficiency of X-band power FETs: 1- low breakdown voltages (< 20 V), and 2- relatively high level of drain-source leakage current near pinch-off. These factors have limited FET power amplifiers to class-A or class-AB operation with drain efficiencies of the order of 50% and power-added efficiencies (PAE) of the order of 40%. In order to improve the power-added efficiency of GaAs FETs to 50% and more, higher efficiency modes such as class-B and class-C are desired. These modes of operation require proper load impedance terminations at the fundamental frequency. Higher efficiency modes (tuned class-B, class-F) are possible through proper design of the load impedance at not only the fundamental frequency but also higher order harmonics. Theoretical analysis [1] shows that the amplifier efficiency is maximized if the even harmonics are terminated into a short-circuit and the odd harmonics into an open-circuit. Tuned class-B power amplifiers at C-band [2] and X-band [3,4] have been reported.

In this paper, we present the results of a study of the effect of second harmonic tuning of power FETs at X-band. Single-stage, hybrid amplifiers were designed and fabricated using 0.5 μm x 1200 μm FETs as the active devices. Theoretical harmonic-balance technique was used to study the effects of bias conditions and harmonic load terminations on the power and efficiency performance of the FETs.

THEORETICAL ANALYSIS

In order to study the effect of load termination at the harmonic frequencies on the efficiency of power FETs at X-band, a large-signal harmonic-balance simulation program [5] was used. The program allows for physical modeling of the active device based on doping profile, material parameters, physical dimensions and bias conditions. The devices used for this study are 0.5 μm x 1200 μm GaAs power FETs fabricated at Texas Instruments. DC and RF small-signal measurements were performed on these devices to verify the validity of the nonlinear FET model. After an accurate nonlinear model was developed for the FETs, the simulation program was used to search for optimum load impedances at the fundamental frequency (10 GHz) and second harmonic. The source impedance was optimized at the fundamental frequency only. Figure 1 shows the simulated PAE of the $1200\mu m$ FET for two different second-harmonic load impedances ($Z_L(2f)$). In both cases the fundamental frequency load impedance was set at the optimum value of 15+j15 Ω. As shown in Figure 1, the analysis shows that terminating the second harmonic by a short while keeping the fundamental frequency load at its optimum value results in a maximum PAE of 65% (drain-efficiency = 75%). However, if the second harmonic is terminated by the same load impedance as the fundamental, the maximum theoretical PAE is 54%. The effect of higher order harmonics is negligible since they are generally less than -30 dBc. The improvement in the PAE due to 2nd-harmonic tuning results from the shaping of the drain current waveform. Figures 2(a),(b) show the large-signal drain current and drain-source voltage, respectively, of the FET for the same two 2nd-harmonic load impedances of Figure 1. As seen in Figure 2, under non-optimized 2nd-harmonic load condition (dashed-dotted line), the current waveform shows a second peak when the drain voltage is at maximum (at about t=38 pS) due to partial breakdown. This component of the current (2nd-harmonic) is

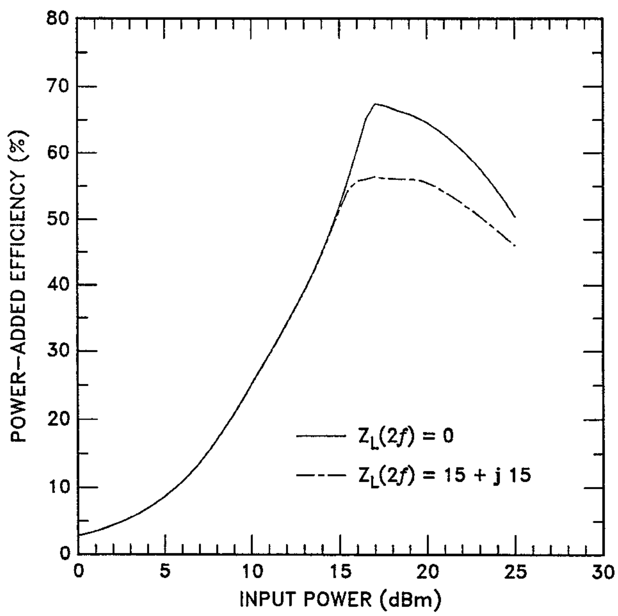

Figure 1: *Calculated power-added efficiency (PAE) of the 1200μm FET for two different 2nd-harmonic (2f) load impedances.*

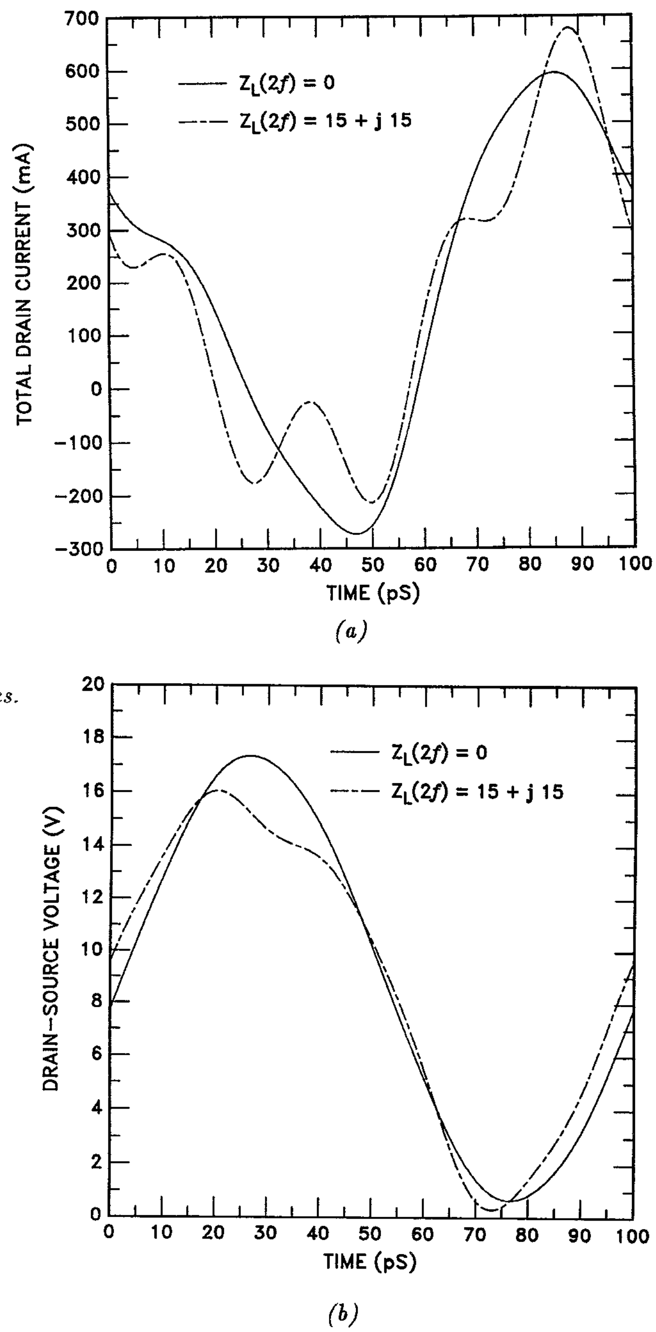

Figure 2: *Drain current (a) and drain-source voltage (b) waveforms of the FET for the same load conditions as in Figure 1.*

IN-PHASE with the drain voltage waveform and thus contributes to power consumption and lowers the efficiency. By terminating the 2nd-harmonic into short, this component of the current is reflected back into the device with the opposite phase and contributes to the power in the fundamental frequency thereby increasing the PAE. The analyis shows that such improvement in the PAE is sensitive to the breakdown voltage and the leakage current near pinch-off.

CIRCUIT DESIGN AND PERFORMANCE

Figure 3 shows the circuit diagram of the amplifier designed to provide, simultaneously, the optimum load impedance at the fundamental and the zero impedance at the 2nd harmonic. A quarter-wave open stub was used for the second-harmonic short. At the fundamental, it becomes capacitive and its capacitance is part of the matching circuit. The inductance in the drain is also optimized to provide the proper reactance to the device. Figure 4 shows the simulated real and imaginary part of the load impedance versus frequency. A near optimum load impedance at the fundamental and short circuit at the second harmonic is attained. Figure 5 shows the measured output power, PAE and drain efficiency of the tuned class-B amplifier. A maximum PAE of 61% with drain efficiency of 76% and 7.4 dB power gain were achieved. The same amplifiers without the second harmonic tuning circuit have demonstrated 50% PAE and 8 dB gain. These results agree very well with the harmonic-balance analysis. The increase in the PAE due to harmonic tuning is at expense of lower power gain and output power density (0.4 W/mm compared to 0.5 W/mm). Figures 6 (a),(b) show the measured spectrum of the amplifier with and without the second harmonic shorting stub at the peak efficiency point. In the absence of harmonic tuning, the 2nd-harmonic content of the amplifier is about -20 dBc whereas for the harmonic tuned amplifier, the 2nd-harmonic level is suppressed to more than 40 dB below the fundamental. The 2nd harmonic suppression was maintained over a 400 MHz bandwidth. This study indicates that a narrow-band tuned class-B amplifier at X-band can be achieved with proper circuit design and an improvement of about 5-10% can be achieved in the PAE using

2nd-harmonic tuning.

SUMMARY

The effects of second-harmonic tuning on the efficiency of power FETs at X-band have been studied. A harmonic-balance simulation program was to find the optimum load impedances at the fundamental and 2nd-harmonic frequencies for 1200 μm FETs at 10 GHz. The theoretical analysis shows 5-10% increase in the power-added efficiency of class-B amplifiers by proper termination of the second harmonic load impedance. This improvement is at the expense of operating voltage and power density. Single-stage, tuned class-B amplifiers were fabricated using 1200 μm power FETs. A power-added efficiency of 61% at an output power level of 450 mW was obtained. The associated power gain and drain efficiency at 10 GHz were 7 dB and 76% ,respectively. The effect of second harmonic tuning will be more significant at lower frequencies (relative to the f_t of the device since the harmonic levels under class-B operation will be larger.

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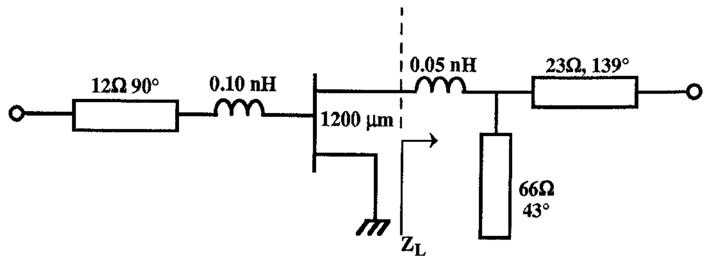

* Electrical lengths are specified at 10 GHz

Figure 3: *Circuit diagram of the tuned class-B amplifier.*

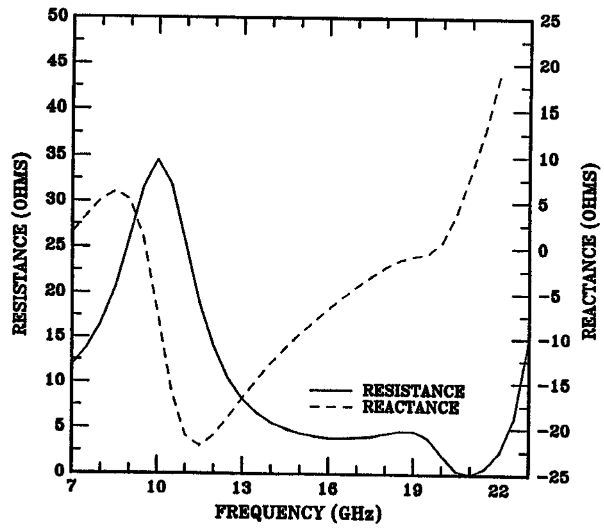

Figure 4: *Simulated real and imaginary part of the load impedance versus frequency.*

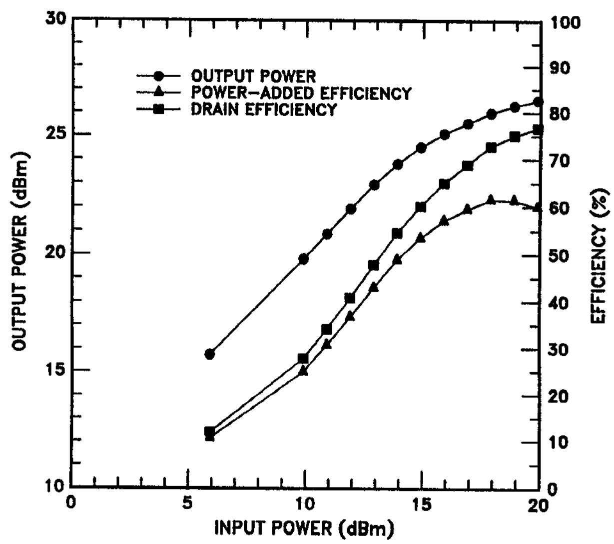

Figure 5: *Measured output power, power-added efficiency and drain efficiency at 10 GHz.*

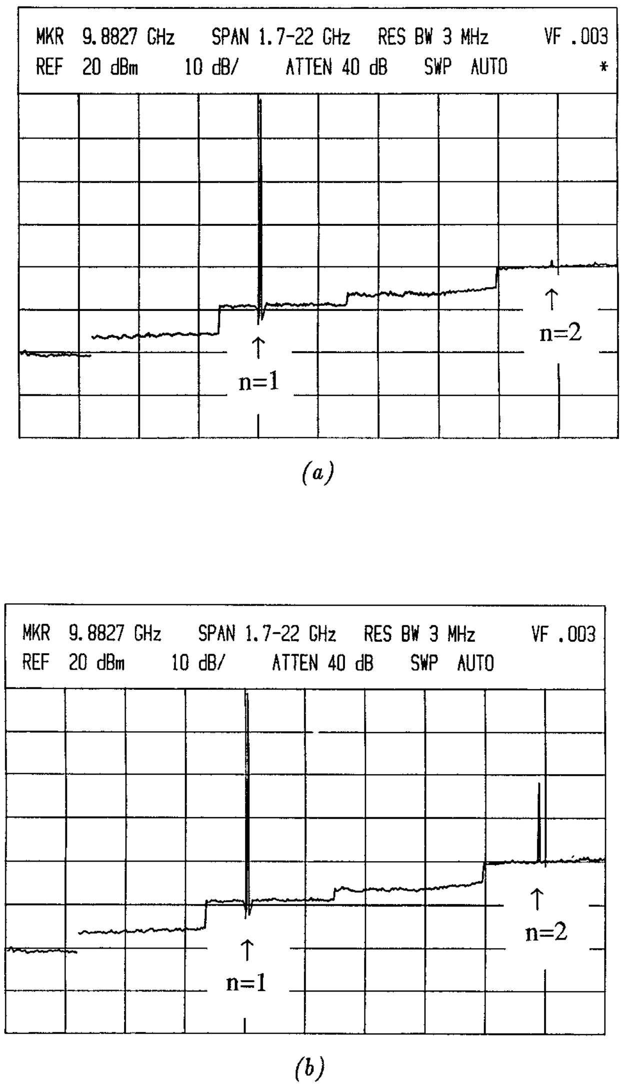

Figure 6: *Measured output spectra of amplifiers with (a) and without (b) second harmonic tuning circuit (span = 1.7 - 22.0 GHz).*