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HIGH EFFICIENCY POWER AMPLIFICATION FOR MICROWAVE AND MILLIMETER FREQUENCIES

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ABSTRACT

A novel technique for realizing high efficiency operation of power amplifiers at microwave frequencies is demonstrated. This appoach features third harmonic peaking Class-F amplifier operation Modeled data indicates this Class-F circuit provides an 8% improvement over the conventional Class-B approach at X-band.

INTRODUCTION

The method of controlling the harmonic loads presented to a transistor for high efficiency amplification is known as Class-F operation.[1] This method, used successfully for years at lower frequencies, is now exploited in microwave amplifiers. Improvements greater than 5% in power-added efficiency have already been demonstrated at X-band by controlling the first three harmonic impedances.[2]

The increase in efficiency results from reduced transistor power dissipation. This increased efficiency is achieved by reducing the time average of the voltage-current product present at the FET. Controlling the harmonics is in essence wave shaping of the voltage and current waveforms at the FET to reduce the overall power dissipated in the FET.

CLASS-F CIRCUIT DESIGN

The method described here for increased power added efficiency is achieved by providing a power match at the first harmonic (fundamental), a short at the second harmonic and an open at the third harmonic. This form of Class-F operation is known as third harmonic peaking. In this amplifier, the transistor is operated close to the Class-B mode, with a drain current waveform of a half rectified sine wave (haversine).

The output circuit is tuned at the fundamental to pass only the fundamental frequency. The second harmonic is short circuited to suppress second harmonic components in the voltage waveform Conversely the third harmonic is open circuited to provide the proper component of third harmonic voltage under optimum rf drive conditions

This third harmonic component causes a flattening of the transistor output voltage waveform, approximating a square wave. Maximum efficiency occurs when the magnitude of the third harmonic component is 1/9 that of the fundamental component as shown in Equation 1.

$$V(t) = V_{D_0} + V_{D_1} * \sin(2\pi\, t/\tau) + V_{D_3} * \sin(6\pi\, t/\tau) \qquad (1)$$

where $V_{D_3} = V_{D_1}/9$ and τ = Period

This equation contains the first three terms of the Fourier series of a square wave. The drain voltage and current waveforms of a third harmonic peaking Class-F amplifier are shown in Figure 1. In this configuration the maximum drain efficiency is calculated to be 88.4%.

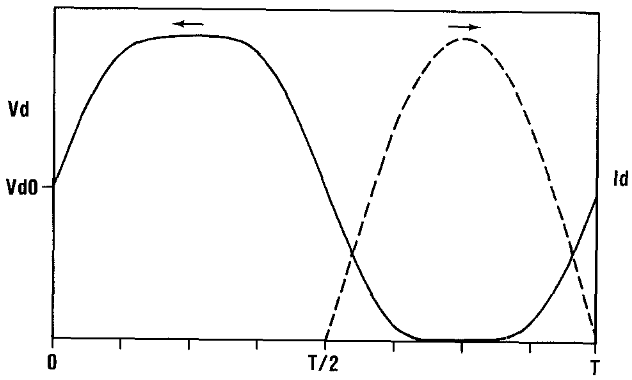

Figure 1. Third Harmonic Peaking Class-F Amplifier Voltage and Current Waveforms.

The output circuit is shown schematically in Figure 2. The harmonic tuning is achieved with C_1, L_1, and C_{ds} of the FET. The fundamental match is provided by Z_1. The short-circuit at the second harmonic is achieved through the series resonance of C_1 and L_1. Let ω_0 be the fundamental frequency, $\omega_2 = 2 * \omega_0$ and $\omega_3 = 3 * \omega_0$, then to realize the short-circuit at the second harmonic

$$L_1 = 1/(\omega_2^2 * C_1). \qquad (2)$$

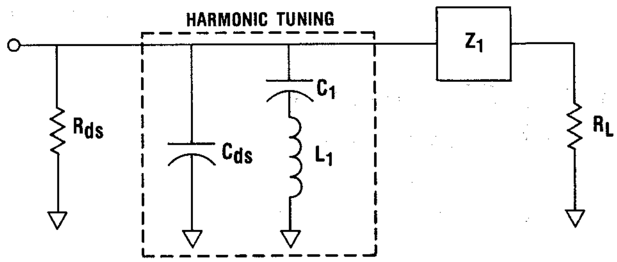

Figure 2. Third Harmonic Peaking Class-F Output Circuit.

The open-circuit at the third harmonic is achieved through the parallel resonance of C_{ds} and the series combination of C_1 and L_1. The harmonic termination at the third harmonic is

$$Z_{Term} = j(\omega_3{}^2 * L_1C_1 - 1)/[\omega_3(C_1 + C_{ds}) - (\omega_3{}^3 * L_1C_1C_{ds})] \quad (3)$$

Upon application of Equation 2 with the fact that Z_{Term} at the third harmonic must be an open-circuit, C_1 and L_1 can be expressed in terms of C_{ds}, such that

$$C_1 = 5/4C_{ds}$$

and

$$L_1 = 1/(5\omega_0{}^2C_{ds}). \quad (4)$$

C_1 and L_1, are normally realized monolithically as a metal-insulator-metal (MIM) capacitor and a short-circuited microstrip transmission line. Recalling the input impedance to a short-circuited transmission line, shown in Figure 3, is described by the relation

$$Z_{in} = jZ_0 \tan\beta l. \quad (5)$$

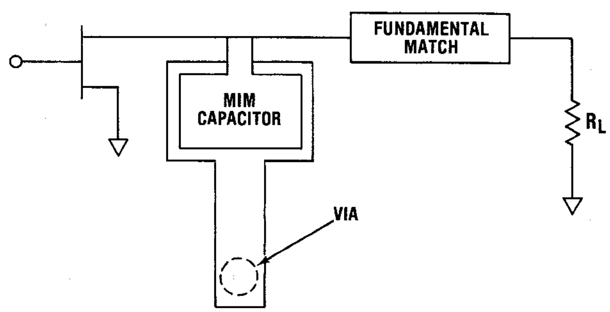

Figure 3. Monolithic Realization of Third Harmonic Peaking Class-F Amplifier Output Circuit.

Finally note that in realizing Z_1 (the fundamental matching circuit) an open circuit at the third harmonic must also be provided. This open circuit impedance at the third harmonic suggests a Low-pass topology for the fundamental matching circuit.

MODELED PERFORMANCE COMPARISON

Verification of the described method for harmonic tuning was accomplished by comparing the performance of a 1200μm FET under Class-B and Class-F conditions on a TI-internal nonlinear simulator using the harmonic balance technique. The characteristics of the 1200μm ion-implanted FET are shown in Table 1. This FET was biased for Class-B operation and matched for maximum power at the fundamental frequency of 10 GHz.

Table 1. 1200μm FET Characteristics

C_{gs}	1.20pF	R_s	0.87Ω	R_i	0.97Ω
C_{gd}	0.55pF	R_g	1.00Ω	I_{dss}	0.385A
C_{ds}	0.33pF	R_d	1.00Ω	V_{po}	-4.20V

The simulated power-added-efficiency (P.A.E) of the FET was 53.7% with 50Ω applied at the 2nd and 3rd harmonic frequencies. The harmonic tuning structure of Figure 2 was realized, using Equation 4, with C_1 = 0.413pF and L_1 = 0.154 nH.

The simulation was repeated using the harmonic tuning circuit under the same bias conditions and fundamental load. The second simulation indicated a power added efficiency of 61.3%. A summary of both nonlinear simulations is provided in Table 2.

Table 2. Nonlinear Simulation Results

Parameter	Class-B	Class-F
Fundamental Load (Ω)	15 + j35	15 + j35
2nd Harmonic Load (Ω)	50	0
3rd Harmonic Load (Ω)	50	0 + j16.15
PIn (dBm)	18	18
POut (dBm)	23.78	24.34
Gain (dB)	5.78	6.34
Vds (Volts)	7.0	7.0
Ids (mA)	47.75	48.87
P.A.E. (%)	53.7	61.3

CONCLUSION

The use of harmonic tuning can have a profound effect on the efficiency of a microwave amplifier. This paper has detailed a novel 3rd harmonic peaking circuit using the drain-source capacitance in conjunction with a series LC resonant circuit to provide maximum power-added-efficiency. The harmonic tuning circuit provided an increase of 8% in power-added-efficiency.

REFERENCES

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

[2] B. Kopp, and D. D. Heston, "High-Efficiency 5-Watt Power Amplifier with Harmonic Tuning," 1988 IEEE MTT International Microwave Symposium Digest, pp. 839-842.