High-Efficiency Load–Pull Harmonic Controlled Class-E Power Amplifier

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***Abstract*— This paper proposes a method to design high-efficiency Class-E power amplifiers following a frequency-domain approach instead of the classical time-domain analysis. Included are equations and plots of universal constant power and efficiency contours of Class-E amplifiers. To validate this method, a 900-MHz Class-E amplifier using a bipolar transistor has been designed and constructed. Power-added efficiency up to 79% and collector efficiency up to 91% have been measured at 900 MHz. Multiharmonic load–pull approach to the design of Class-E amplifiers proves that Class-E operation is possible at microwave frequencies using bipolar technology.**

***Index Terms*—Class-E, high-efficiency amplifier, load–pull.**

I. Introduction

To date, most Class-E amplifiers have been designed for low-frequency applications. Therefore, except for [1], the rest of the classical approaches [2], [3] to the Class-E amplifier have been carried out in the time domain. The classical output network for Class-E operation [2] exhibits different problems when it is used at high frequencies. Usually, the load resistance needed in the classical output network is not 50 Ω. So, in order to match an amplifier using that classic network to a 50-Ω system, a transformer or another matching network with suitable frequency behavior is needed. The effects of matching on efficiency, output power, and class of operation of power amplifiers have been established [4], and it has been shown that the frequency behavior of certain output matching networks can lead to Class E or C-E. A simple method to find the load impedance to achieve Class-E operation is described in this work.

II. Analysis

High-frequency solid-state devices exhibit several problems operating in the Class-E mode, namely nonideal switching, nonlinear capacitance at the output, and package effects. Previous works [3] have shown that these undesirable effects, if they are under control, do not preclude Class-E operation at high frequencies. It is difficult, however, to measure and model these effects, and accurate models are not available. Therefore, an approximate design method of Class-E amplifiers at high frequencies could be very useful.

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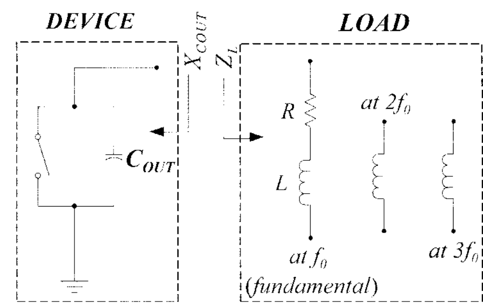

Fig. 1. Load to achieve Class-E operation.

Besides switching problems, the most important limitation to Class-E operation in the microwave region is the internal capacitance of the device C_{OUT} [5] which includes intrinsic nonlinear capacitances and package effects. Usually, at radio frequency (RF) $X_{C\mathrm{OUT}}$ (the reactance of C_{OUT}) is sufficient, sometimes more than sufficient, to allow Class-E operation in the terms described in the classic references [2]. In this situation, it is possible to work in Class E, setting an adequate load at the fundamental frequency and strong reactive load at the second and third harmonic, as indicated in Fig. 1.

These load requirements can be fulfilled using any output network made of lumped elements, transmission lines, etc., with the only condition that it provides the required load at fundamental and harmonic frequencies. Once the device is heavily overdriven, (1)—derived from [2] and [3]—is a good approximation for predicting the load Z_L at the fundamental frequency:

$$Z_L \simeq R[1 + 1.152]. \tag{1}$$

The value of R can be obtained from [2], [3]

$$R = 0.58\frac{(V_{cc} - V_{CE(\mathrm{sat})})^2}{P_E}. \tag{2}$$

The classical low-frequency approach to Class-E design also imposes a relation between Z_L and $X_{C\mathrm{OUT}}$, given by

$$\frac{Z_L}{|X_{C\mathrm{OUT}}|} = 0.183 + 0.211j. \tag{3}$$

It is not easy, however, to satisfy the (3) at RF because of the low value of $X_{C\mathrm{OUT}}$ inherent to most RF devices. In this situation, it is still possible to obtain very high collector efficiency at the expense of output power. Fig. 2 shows a set of curves of constant collector efficiency and constant output power versus $Z_L/X_{C\mathrm{OUT}}$ at the fundamental frequency. Harmonic load is kept strongly reactive.

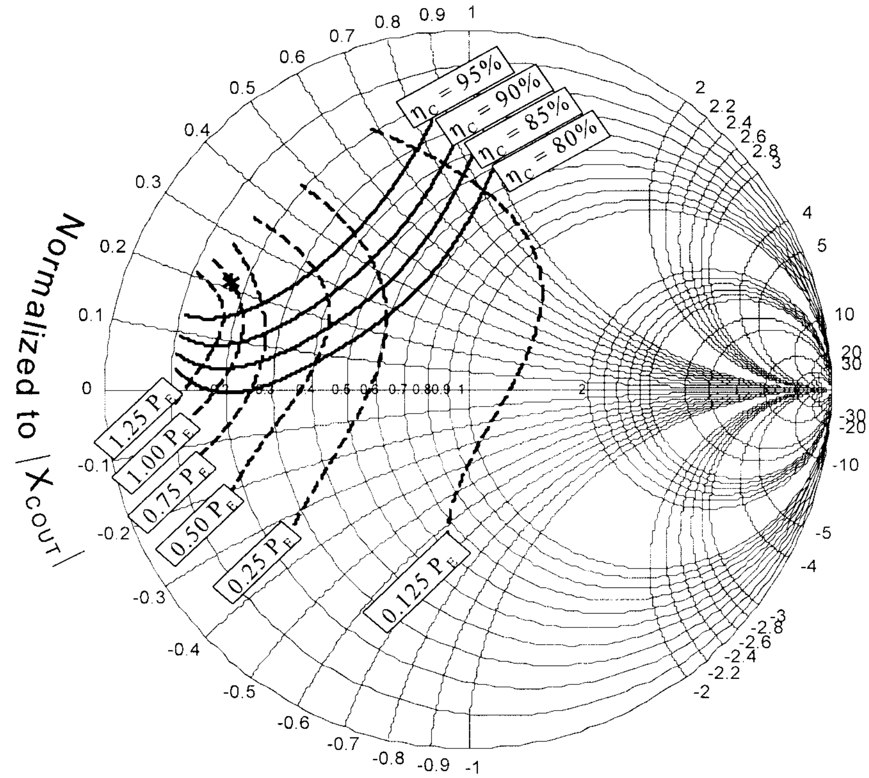

Fig. 2. Constant efficiency an constant power contours.

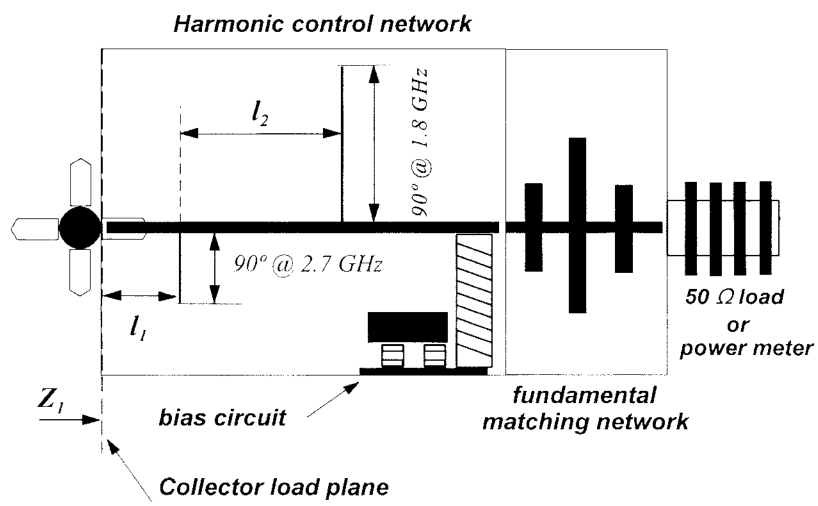

Fig. 3. Harmonic-controlled text fixture.

These curves have been obtained using the circuit of Fig. 1 and nonlinear time domain simulation. In order to reproduce the most usual situation in RF, $C_{\rm OUT}$ has been modeled by a fixed value linear capacitor (equivalent of the actual nonlinear one) across the collector and the emitter of the transistor. The load Z_L at f_O, the fundamental frequency, has been changed while keeping the load at $2f_O$ and $3f_O$ strongly reactive and the value of $C_{\rm OUT}$ fixed. A very simple static Ebers–Moll model has been used for the transistor (which is kept heavily overdriven during the process). The transistor reaches forward saturation, reverse saturation, and cutoff regions during the simulations. More than 500 loads have been simulated. The results in Fig. 2, plotted on a Smith Chart normalized to $X_{C\rm OUT}$, show efficiency and output power versus $Z_L/X_{C\rm OUT}$. The power plots are normalized to the output power P_E obtained from a classic Class-E amplifier using the relations given in (1)–(3).

The plots of constant collector efficiency show that it is possible to achieve a very high collector efficiency $(\eta_C > 90\%)$, even with values of $C_{\rm OUT}$ higher than the values established in classical theory [2], [5], at the expense of lower output power than that predicted for classic Class-E operation. So, the frequency range of the classic Class-E amplifier can be exchanged for output power.

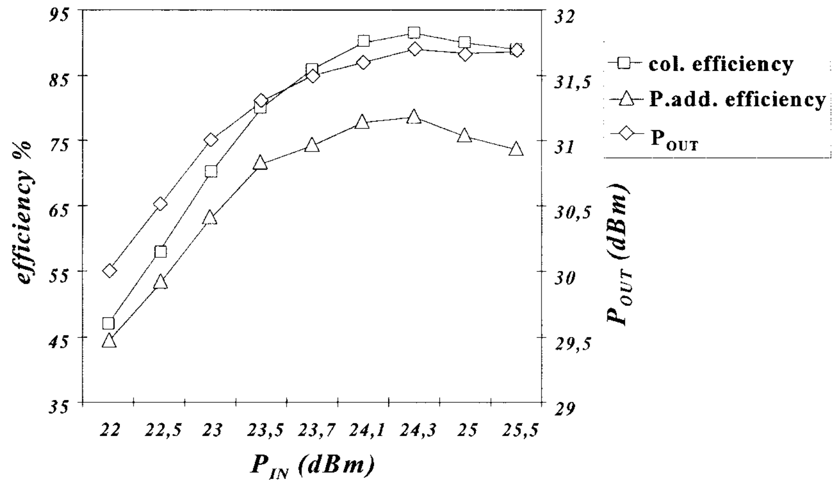

Fig. 4. Amplifier's output power and efficiency.

TABLE I
PERFORMANCE OF THE CLASS-E AMPLIFIER

Maximum Power	1.5 W
Maximum efficiency (added)	79%
Maximum efficiency (collector)	91%
Gain for maximum efficiency	7.2 dB
Current for maximum efficiency	130 mA

III. VALIDATION

To validate these results a demonstration amplifier has been constructed using the commercial bipolar transistor MRF557. There are several variables in practice that, for simplicity, are not taken into account by the previous equations and curves, namely collector switching fall time t_f, saturation resistance voltage, etc. The test fixture showed in Fig. 3 was used to implement the amplifier.

A "harmonic control network" provides control of the load impedance at the second and third harmonic. The "harmonic control network" is made of open-circuited $\lambda/4$ stubs at the second and third harmonic. Controlling the location of these stubs a short circuit at the second or third harmonic is presented at the collector line of the transistor. Usually, the $3f_o$ stub is located before the $2f_o$ stub as shown in Fig. 3. The load impedance at $2f_o$ and $3f_o$ presented by the test-fixture can be calculated using a set of equations available from the authors.

IV. RESULTS

Fig. 4 shows the amplifier output power and efficiency versus input power at 900 MHz. Table I shows the performance of the amplifier (the maximum ratings are not obtained simultaneously).

V. CONCLUSIONS

A Class-E amplifier using bipolar technology is possible at high UHF band. A method to achieve Class E has therefore been proposed that predicts the collector efficiency and output power of a Class-E amplifier for a determinate Z_L/X_{COUT} relation when the load at the harmonics is strongly inductive, and the active device is heavily overdriven. As a demonstration a Class-E power amplifier has been designed and constructed following the proposed method with the excellent results $\eta_C = 90\%$ @ 900 MHz.

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