

# High-efficiency parallel-circuit class-E power amplifier with distributed T-shaped compensation circuit

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**Abstract:** This article reports a modified parallel-circuit class-E power amplifier (PA) that maintains its operating conditions even when the output capacitance of the transistor is greater than the optimum capacitance. The finite inductor in the parallel topology is replaced by an L-C T-shaped circuit to eliminate the limits on the maximum operating frequency. The L-C T-shaped circuit can be approximately transformed to the distributed for the microwave applications. The analysis is validated by simulation and measurement. The fabricated PA delivers a maximum drain efficiency of 77.5% with the maximum output power of 40.2 dBm at 2.9 GHz.

**Keywords:** power amplifier (PA), parallel-circuit class-E, high efficiency, enhanced maximum operating frequency

**Classification:** Microwave and millimeter-wave devices, circuits, and modules

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## 1 Introduction

The power amplifier (PA) remains a critical component in mobile/wireless communication systems, since it is an important energy consumer that significantly impacts the overall power consumption budget of a mobile/wireless transmitter. Consequently, designing high-efficiency amplifiers is of prime importance to reduce power consumption, cooling requirements, and cost in mobile/wireless transmitter and to improve reliability aspects. Various efficiency enhancement techniques have been studied, such as class E [1, 2, 3, 4], class-F [2, 3, 4], class-J [3], and so forth. Among these techniques, the class-E PA is considered as one of the best candidates in RF and microwave PA applications [2, 3, 4, 5], due to its simplicity and high efficiency.

The class-E PA, proposed by Sokals [1] and subsequent developed by Raab [3], can offer high efficiency by tailoring the transient response of the voltage and current waveforms to minimized energy loss at the switching instants. In 2002, Grebennikov *et al.* proposed the parallel-circuit class-E PA, which exhibits a maximum operating frequency 1.4 larger than the conventional class-E PA with shunt capacitance [5]. The maximum operating frequency  $f_{\max}$  of the class-E/parallel-circuit class-E PA is the intrinsic limitation due to the transistor output capacitance  $C_{\text{out}}$  [5, 6].

In order to achieve the high efficiency of the class-E PA beyond  $f_{\max}$ , some methods have been proposed introducing an inductor to compensate the excessive capacitance reactance  $C_{\text{ex}}$  [7, 8, 9, 10]. However, the main focus of the most approaches is only to investigate how to compensate for  $C_{\text{ex}}$  at a single frequency, such as the fundamental frequency [7, 8]. As a consequence, the open-circuit requirement at higher harmonics for optimum Class-E operation would be violated, which has a detrimental effect on the amplifier performance at high frequencies. To resolve this issue, some methods have been proposed to compensate the output capacitance at both the fundamental and harmonic frequencies [9, 10]. However, the method in [9] has been restricted to only being used in low-frequency applications, due to large parasitic parameters at high frequencies and self-resonant

frequency of the lumped components. In [10], a transmission-line compensation circuit is proposed, which is more suitable for microwave band. However, the implementation of the compensation circuit is complex, since the short-circuited shunt stub has to be designed using a stub terminated with a large capacitor, to realize RF ground. It would be better, if possible, to develop a unified design strategy that can be simultaneously suitable for low and high frequencies with a low circuit complexity.

To overcome these practical design problem, a unified compensation technique for parallel-circuit class-E has been developed to compensate the output capacitance at both the fundamental and harmonic frequencies. The L-C T-shaped network is utilized to replace the finite DC feed inductor in parallel circuit to eliminate the limits on the operating frequency imposed by the output capacitance. To be suitable for microwave applications, the L-C T-shaped circuit can be approximately transformed to a distributed circuit with low complexity.

## 2 Parallel-circuit class-E with enhanced $f_{\max}$

A parallel-circuit class-E PA is shown in Fig. 1. If we assume that losses in the reactive circuit elements are negligible, the quality factor of the loaded  $L_0$ - $C_0$  circuit is high. The values for circuit elements and the maximum operating frequency can be obtained from [4, 5]

$$R = 1.365 \frac{V_{DD}^2}{P_{out}} \quad (1)$$

$$L = 0.732 \frac{R}{\omega} \quad (2)$$

$$C = \frac{0.685}{\omega R} \quad (3)$$

$$f_{\max} = 0.0798 \frac{P_{out}}{C_{out} V_{DD}^2} \quad (4)$$

Eq. (4) shows the relationship between  $f_{\max}$ ,  $P_{out}$ ,  $V_{DD}$ , and  $C_{out}$ . It is clear that  $f_{\max}$  and  $C_{out}$  are inversely related. In most cases, the value of  $P_{out}$  is fixed and the value of  $V_{DD}$  can be chosen within an operational range. Therefore, the transistor's output capacitance is the main factor limiting  $f_{\max}$ . A feasible and effective method to reduce this limitation is to compensate for  $C_{ex}$  with an external circuit.

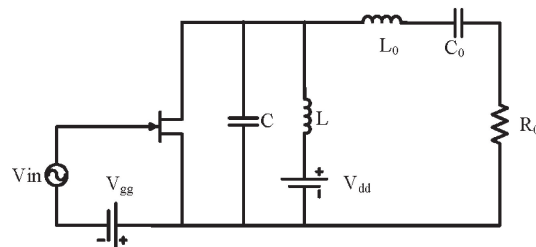
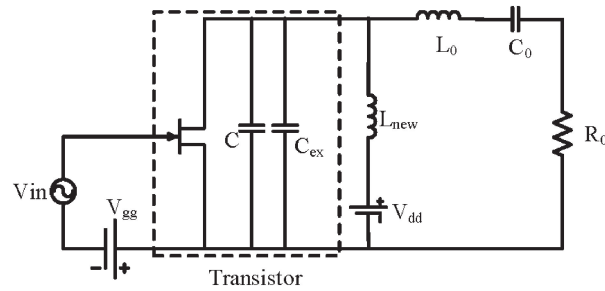


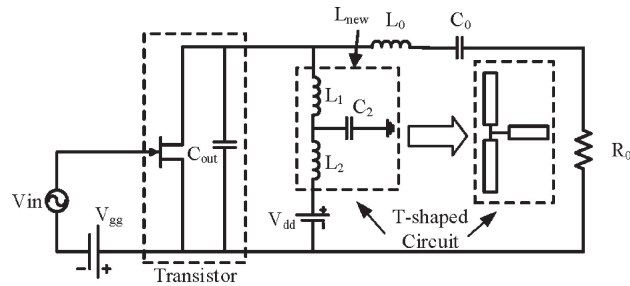
Fig. 1. Basic circuit of parallel circuit class-E PA.

In the following, it is assumed that the output capacitance of the transistor  $C_{out}$  is larger than the optimum value obtained from Eq. (3), i.e.,  $C_{out} = C(1 + \alpha)$ , where  $\alpha = C_{ex}/C$  is defined as the excess factor [9, 10]. When  $\alpha > 0$ , a different value of the feed inductor  $L_{new}$  is required as depicted in Fig. 2. The value of  $L_{new}$  should be chosen so as to compensate for the capacitive susceptance of  $C_{ex}$  both at the fundamental frequency and at the harmonic frequencies. Thus, the net susceptance of  $C_{ex}$  and  $L_{new}$  should have the same values of  $L$  for all  $\omega$ , i.e.,

$$\frac{1}{j\omega L} = j\omega C_{ex} + \frac{1}{j\omega L_{new}} \quad (5)$$



**Fig. 2.** Parallel circuit class-E PA with excess capacitance.



**Fig. 3.** Lumped and transmission-line T-shaped compensation circuit of the proposed class-E PA.

Therefore, the value of the required inductor  $L_{new}$  is frequency dependent, which is obtained to

$$L_{new} = \frac{L}{1 + 0.5\alpha \left( \frac{\omega}{\omega_0} \right)^2} \quad (6)$$

The load impedances seen at the  $C_{out}$ -plane, as depicted in Fig. 2, can be written as follows [10, 11]:

$$Z_L(\omega_0) = R \parallel j\omega_0 L_{new} = R \cdot \frac{1 + j1.366(1 + 0.5\alpha)}{1 + j1.866(1 + 0.5\alpha)} \quad (7)$$

$$Z_L(n\omega_0) = jn\omega_0 L_{new} = j \frac{n\omega_0 L}{1 + 0.5\alpha n^2} \quad (8)$$

It is possible to achieve optimum parallel-class E operating conditions by replacing the value of the inductor  $L$  obtained in Eq. (2) with the value of  $L_{new}$  obtained in Eq. (6).

### 3 Design method of the new inductor

A simplified topology with a lumped-element T-shaped L-C network composed of two series inductors and one parallel capacitor is proposed, as depicted in Fig. 3. Moreover, this circuit can be used to the drain bias line. The input impedance of the T-shaped network can be obtained as a function of the frequency:

$$Z_T(n\omega_0) = j \left[ n\omega_0 L_1 + \frac{n\omega_0 L_2}{1 - (n\omega_0)^2 L_2 C_2} \right] \quad (9)$$

The equations relating the values of the components to the excess factor  $\alpha$  can be obtained by equating the input impedance of the T-shaped network to the impedances in Eq. (8) for  $n = 1$  and  $n = 2$  as follows:

$$\frac{\omega_0 L}{1 + 0.5\alpha} = \omega_0 L_1 + \frac{\omega_0 L_2}{1 - \omega_0^2 L_2 C_2} \quad (10)$$

$$\frac{\omega_0 L}{1 + 0.5\alpha} = \omega_0 L_1 + \frac{\omega_0 L_2}{1 - \omega_0^2 L_2 C_2} \quad (11)$$

The resonant frequency  $\omega_2$  of the  $L_2 C_2$  fulfills  $\omega_0 < \omega_2 < 2\omega_0$ , and can be related to the fundamental frequency by means of a new parameter denoted here as  $\gamma$

$$\gamma = \left( \frac{\omega_0}{\omega_2} \right)^2 \quad (12)$$

The values of  $L_1$ ,  $L_2$  and  $C_2$  can be solved

$$L_1 = \frac{L(2\gamma + \alpha)}{\gamma(2\alpha^2 + 5\alpha + 2)} \quad (13)$$

$$L_2 = -\frac{\alpha L(4\gamma^2 - 5\gamma + 1)}{\gamma(2\alpha^2 + 5\alpha + 2)} \quad (14)$$

$$C_2 = \frac{\gamma}{\omega_0^2 L_2}. \quad (15)$$

In special applications, when it is difficult to implement a long transmission line, for example, in monolithic integrated circuits or low-frequency applications, it is possible to consider a class-E PA based on the lumped-element circuits. However, use of this compensation technique in the microwave band is restricted by the lumped-element chip capacitors and inductors due to self-resonance frequencies of these chip devices. Therefore, a lumped T-shaped circuit has to be transformed into a distributed circuit. The conversion of the lumped T-shaped circuit involves replacing the series inductances and shunt capacitances with equivalent transmission-line elements. The series inductances can be realized by short sections (less than  $\lambda/8$ ) of a high-impedance line, and shunt capacitors by lower impedance open-circuit stubs by Eqs. (16) and (17) [11], as shown in Fig. 3.

$$\omega L \approx Z_l \Rightarrow l \approx \frac{v_p L}{Z_l} \quad (16)$$

$$\frac{1}{\omega C} = \frac{Z_c}{\tan \beta l} \Rightarrow l = \frac{\arctan(Z_c \omega C)}{\beta} \quad (17)$$

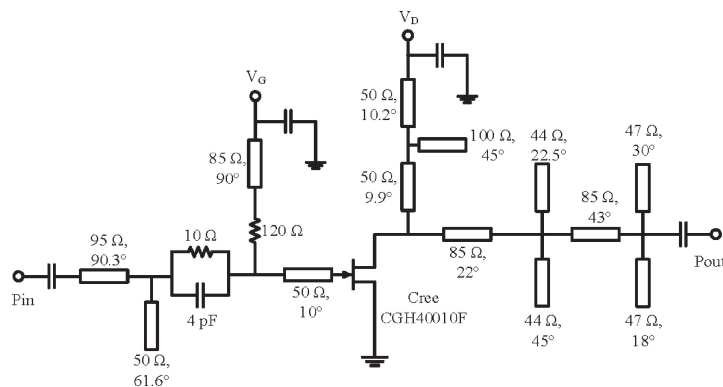
where  $Z_l$  and  $Z_c$  are the characteristic impedance of the lower impedance line and high-impedance line respectively and  $\beta$  and  $v_p$  are the propagation constant and phase velocity of the transmission line, respectively.

#### 4 Circuit design and measurement results

To verify the proposed topology, a parallel-circuit class-E PA with the T-shaped transmission-line is designed using a 31mil RO5880 substrate. The switch is replaced by a Cree GaN HEMT power device (CGH40010F), whose parameters are listed in Table I. The theory parameter values of the parallel class-E PA are shown in Table I.

**Table I.** Circuit parameters of parallel-circuit class-E

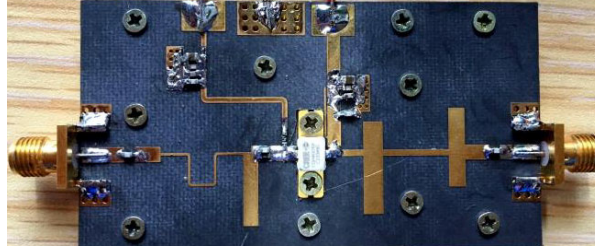
Parameter	Value	Parameter	Value
Device	CGH40010F	$R$	92.3 $\Omega$
Frequency	3 GHz	$L$	3.58 nH
$V_{DD}$	28 V	$C$	0.40 pF
$C_{out}$	1.5 pF	$C_{ex}$	1.1 pF
$P_{out}$	10 W	$\alpha$	2.75



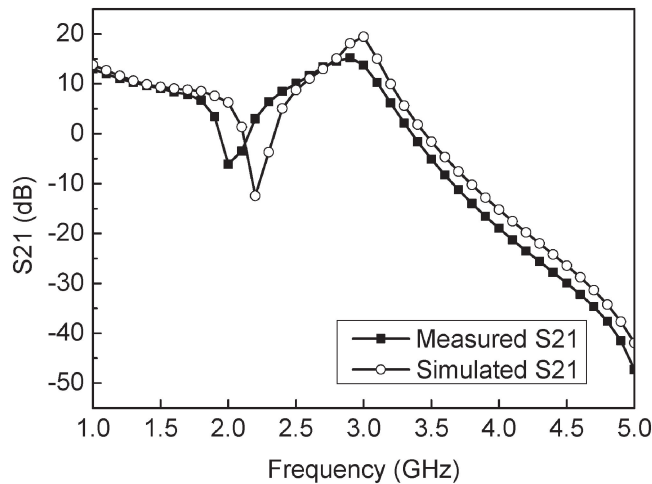
**Fig. 4.** Full schematic of the proposed class-E PA.

Fig. 4 shows the full schematic of the class-E PA. The input matching network provides a complex-conjugate matching at the operating frequency in order to achieve low insertion loss using an L-Type topology. The series R-C network and the resistor connected with the gate bias line construct the stable circuit. The output matching network is designed convert the standard 50- $\Omega$  impedance into an optimum impedance of 92.3  $\Omega$ . This is realized by using a transmission-line load network which offers combined transformation of the load resistance to a suitable level, as well as simultaneous suppression of harmonics in the load. The drain bias circuit is accomplished by a T-shaped transmission-line circuit, which is designed using the above method.

Fig. 5 depicts the photograph of the fabricated PA mounted on a heat sink. The total size of the module is 9.5 cm  $\times$  4 cm. The device is biased with a drain voltage of 28 V and a gate voltage of  $-2.8$  V. It should be noted that due to variations in the



**Fig. 5.** Photograph of the fabricated class-E PA.



**Fig. 6.** Simulated and measured small-signal gains of the proposed class-E PA.

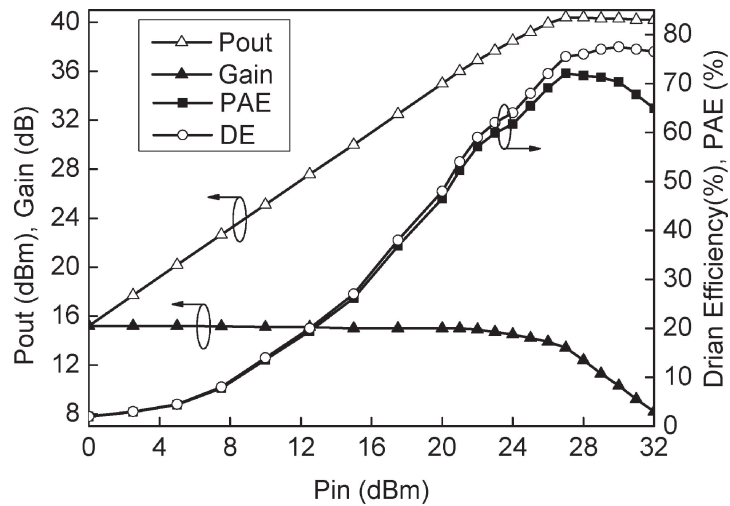
threshold voltage and electron mobility of transistor, the required gate bias voltages to maintain same bias currents in the measurement and simulation are slightly different.

Fig. 6 shows the simulated and measured small-signal gains of the proposed class-E PA under small-signal conditions. The simulated and measured results are in good agreement from 1 GHz to 5 GHz. The proposed PA features the maximum small-signal gain of 15.5 dB at 2.9 GHz, which is slightly shifted from the simulated design frequency (3 GHz).

The large-signal continuous-wave (CW) performance is measured by a power spectrum analyzer FSV40. The measured output power, gain, drain efficiency (DE), and PAE against RF input power are illustrated in Fig. 7. A peak drain efficiency of 77.5% and a peak PAE of 72.2% were obtained at the frequency of 2.9 GHz and at an output power of 40.2 dBm. The RF input power applied to the PA was 28 dBm, yielding 12.2 dB gain. The measured optimum frequency (2.9 GHz) shifted from the simulated design frequency (3 GHz) mainly due to the inaccurate large-signal model of the transistor, as well as fabrication tolerances of the substrate's dielectric constant and surface-mount technology (SMT) passive components.

Table II compares the performance of the designed class-E PA to those of recently reported microwave PAs operated in class-E mode using packaged GaN HEMT devices with similar or close output power. It is evident that the proposed parallel-circuit class-E PA products state-of-the-art performance at higher frequency.





**Fig. 7.** Measured output power, gain, drain efficiency (DE), and PAE against RF input power.

**Table II.** Performance summary of various class-E PAs with GaN HEMT packaged transistors

Ref.	$f_0$ (GHz)	PAE (%)	Pout (dBm)	Gain (dB)
[7]	2.14	70	37.5	13
[9]	0.428	78.6	37.5	16.5
[10]	2.8	70.8	40.1	10.7
This work	2.9	72.2	40.2	12.2

## 5 Conclusion

This paper presents a unified compensation technique for parallel-circuit class-E that can be simultaneously suitable for low- and high-frequency applications. An L-C T-shaped network is utilized to replace the finite DC feed inductor in parallel circuit topology to eliminate the limits on the maximum operating frequency. To be suitable for microwave applications, the L-C T-shaped circuit can be approximately transformed to a distributed circuit and simplify the circuit complexity. By adding dynamic bias control, this PA can also be used for signals with varying envelopes.

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