High-efficiency class E/F₃ power amplifiers with extended maximum operating frequency

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Abstract: This paper presents high-efficiency class-E/F₃ power amplifiers with extended maximum operating frequency \( f_{\text{max}} \) using a novel method of a transmission-line compensation circuit (TLCC). Theoretical analysis is presented in order to obtain circuit component values, which compensate the excess output capacitance \( C_x \) and satisfy the required impedances of the class-E/F₃ power amplifiers at the fundamental frequency and harmonics. The proposed circuit, whose \( f_{\text{max}} \) is 4 times higher than the conventional structure, has been designed, fabricated, and measured. Besides, high-performance results with the output power of 40.3 dBm, drain efficiency of 82.9% have been achieved.

Keywords: class-E/F₃, high-efficiency power amplifier (PA), maximum operating frequency, transmission-line compensation circuit (TLCC)

Classification: Power devices and circuits

References


1 Introduction

With the rapid development of RF transmission systems, it is gradually required that power amplifiers (PAs) operate with high efficiency, high output power, good linearity and so on. Among these requirements, high-efficiency is the most critical one, especially in high power or battery-powered applications [1]. Therefore, it has been a hot topic to develop high-efficiency PAs.

The class-E PA is one of the well-known high-efficiency PAs due to its relatively simple realization and elimination of turn-on switching losses because of a soft-switching operation mode [2, 3]. However, as far as the peak drain voltage \(V_{\text{max}}\) is concerned, the class-E approach is not a good choice for practical applications because of the relatively large switch stresses to active devices, especially in the integrated circuit [4]. Fortunately, differing from the class-E PA, the class-F/F\(^{-1}\) PA has lower \(V_{\text{max}}\) and higher attainable operating frequencies [5]. Whereas, due to the tuning requirements [6, 7] and the lack of a simple circuit implementation, e.g., [8], the class-F/F\(^{-1}\) PA also has performance limitations. Based on the advantages and disadvantages in class-E PA [2, 3, 4] and class-F/F\(^{-1}\) PA [5, 6, 7, 8], it is of great significance to combine the two high-efficiency PAs and present a new PA mode of operation: class-E/F\(^3\) PA [9, 10, 12, 13, 14, 15], which not only realizes a relatively simple structure, but also reduces the peak voltage \(V_{\text{max}}\) [9, 10]. However, in the class-E/F\(^3\) power amplifier, the optimum shunt capacitance \(C\) decreases with the increase of the maximum operating frequency \(f_{\text{max}}\), is defined as the maximum frequency at which the device output capacitance \(C_{\text{out}}\) can provide the shunt susceptance \(B_{\text{opt}}\) required for optimum operation [11] for the prescribed output power \(P_0\) and DC supply voltage \(V_{\text{DS}}\) [12, 13]. In practical applications, \(C\) becomes smaller than \(C_{\text{out}}\) in the high \(f_{\text{max}}\) [14], which results in excess output capacitance \(C_x (= C_{\text{out}} - C)\). Owing to this, the class-E/F\(^3\) PA operates at a suboptimal condition and its efficiency consequently decreases a lot [15]. In a word, the \(f_{\text{max}}\) of the conventional class-E/F\(^3\) PA is limited to hundreds of MHz when keeping its optimal mode of operation, thus representing a crucial issue.

In this paper, in order to further increase the \(f_{\text{max}}\) of a class-E/F\(^3\) power amplifier to GHz when operating at an optimal condition, a novel method of a transmission-line compensation circuit (TLCC) is proposed. This structure com-
pensates $C_x$ at both the fundamental and harmonic frequencies. Therefore, the TLCC bypasses the limitations on $f_{\text{max}}$ of the class-E/F3 PA. Besides, a high performance PA, whose $f_{\text{max}}$ is 4 times larger than the conventional structure, is designed and fabricated to validate the theory. In brief, due to its extended $f_{\text{max}}$, simple construction and low-loss implementation at high frequencies, the proposed circuit is more suitable for use as a class-E/F3 amplifier operating in the microwave band.

2 Class-E/F3 PAs

2.1 Standard idealized class-E/F3 PAs

The circuit schematic of the idealized class-E/F3 PA is depicted in Fig. 1. The transistor must be driven sufficiently hard such that it operates like a switch rather than a current source. The series-tuned resonator $L_0C_0$ and the series resonant $L_nC_n$ circuit are tuned at the fundamental and the third harmonic, respectively. Meanwhile, the quality factors of them are sufficiently high. The optimal load impedances at the fundamental frequency and higher harmonics seen by the transistor, $Z_{\text{opt}}$, are given in (1). The loading network presents $R$ in series with $L$ at $f_0$, an open circuit at all harmonics except the third harmonic, and a short circuit at the third harmonic. For the prescribed output power $P_0$, DC supply voltage $V_{\text{DS}}$, and operating frequency $f_0$, the optimal load resistance $R$, series inductance $L$ and shunt capacitance $C$ can be calculated using (2), (3) and (4). Besides, the expression for $f_{\text{max}}$ can be obtained like (5).

$$Z_{\text{opt}} = \begin{cases} R + j\omega_0L, & \text{at } f_0 \\ 0, & \text{at } 3f_0 \\ \infty, & \text{at } nf_0; n = 2, 4, 5 \ldots \end{cases}$$

$$R = 0.657 \frac{V_{\text{DS}}^2}{P_0}$$

$$\frac{\omega_0L}{R} = 0.961$$

$$\omega_0CR = 0.209$$

$$f_{\text{max}} = 0.0506 \frac{P_0}{CV_{\text{DS}}}.$$
Ideally, the shunt capacitance $C$ can entirely furnish the device output capacitance $C_{\text{out}}$. By substituting $C = C_{\text{out}}$, $f_{\text{max}}$ can be rewritten as

$$f_{\text{max}} = 0.0506 \frac{P_0}{C_{\text{out}} V_{DS}^2}.$$  \hspace{1cm} (6)

### 2.2 Class-E/F$_3$ PA with extended $f_{\text{max}}$

From (5), it follows that $C$ decreases with the increase of $f_{\text{max}}$ for the prescribed $P_0$ and $V_{DS}$. In practical applications, $C$ becomes smaller than the device output capacitance $C_{\text{out}}$ in the high $f_{\text{max}}$, which results in excess output capacitance $C_x$ ($= C_{\text{out}} - C$). The enhancement of $f_{\text{max}}$ is achieved by compensating $C_x$. This translates into higher $f_{\text{max}}$ expressed in (7) as follows, where $C_x$ is defined as $KC$ ($K > 0$):

$$f_{\text{max}} = 0.0506 \frac{P_0}{(C_{\text{out}} - C_x)V_{DS}^2}$$

$$= 0.0506(1 + K) \frac{P_0}{C_{\text{out}} V_{DS}^2}.$$  \hspace{1cm} (7)

Compared with the original result given in (6), $f_{\text{max}}$ is increased by $1 + K$ times, which can be realized by the proposed TLCC given in Section 3.

### 3 TL compensation circuit for class-E/F$_3$ PA

Some methods including a lumped-element equivalent circuit [16], and TLCC [17] have been presented to compensate $C_x$ and extend $f_{\text{max}}$ in other high-efficiency switch-mode PAs. However, the method in [16] has been restricted by the lumped-element model and large parasitic losses at high frequencies [17]. Therefore, as described in Fig. 2, a new class-E/F$_3$ PA circuit topology with TLCC is proposed in this paper. Due to the advantage of the proposed TLCC, it is convenient to satisfy the impedance conditions for both the fundamental and harmonics without any other redundant circuits.

In order to simplify the problem, three reference points (A, B, C) are placed in Fig. 2. The characteristic impedances and electrical lengths of the cross-junction TL$_1$–TL$_4$ are $Z_1$, $Z_1$, $Z_2$, $Z_2$ and $45^\circ$, $75^\circ$, $45^\circ$, $45^\circ$, respectively. At second harmonic
frequency, the cross-junction can provide an open termination at the point B. At the third harmonic, TL₁ resonates with TL₂ in order to provide an open-circuit at the point A. Therefore, the cross-junction seen by the point B at the third harmonic can be simplified as a $3\lambda/4$ transmission-line, which can provide a short termination so as to satisfy the condition of the harmonic impedance like (1).

Furthermore, the electrical length of the drain biasing TL₆ in Fig. 2 is $90^\circ$ and it consequently provides a short-circuit termination at $2\omega_0$. Thus, the shorted series line TL₅ behaves like an inductance $L_a$ at the second harmonic

$$jZ_3 \tan(2\theta_3) = j2\omega_0 L_a.$$  \hspace{1cm} (8)

where, $\theta_3$ and $Z_3$ are the electrical length and characteristic impedance of TL₅, respectively. This inductance $L_a$ must be resonated with $C_x$ at the point C, in order to compensate $C_x$ and provide the required open circuit for the second harmonic like (1), and hence

$$j2\omega_0 C_x + \frac{1}{j2\omega_0 L_a} = 0.$$  \hspace{1cm} (9)

Note that there are two degrees of freedom $(\theta_3, Z_3)$. Taking the fourth harmonic into consideration, it is better to select $22.5^\circ$ as the electrical length of TL₅ because of its open-circuit termination for the fourth harmonic at the point C. Thus, the characteristic impedance of TL₅ can be determined by (8)–(9).

At $4\omega_0$, since TL₁ and TL₃ represent the open-circuited terminations at the point A, the cross-junction at the point B can be simplified as an inductance $L_b$:

$$\frac{Z_1}{j \tan(75 \times 4)} = j4\omega_0 L_b.$$  \hspace{1cm} (10)

Then, like the compensation for the second harmonic, the inductance $L_b$ must be resonated with $C_x$ at the point C, in order to compensate $C_x$ and provide the required open circuit for the fourth harmonic like (1), and hence

$$j4\omega_0 C_x + \frac{1}{j4\omega_0 L_b} = 0.$$  \hspace{1cm} (11)

The characteristic impedance $Z_1$ of TL₁–TL₂ can be determined by (10)–(11).

It should be noted that the electrical length of TL₂ is $75^\circ$ rather than $15^\circ$ at the fundamental. Although TL₂ with electrical length of $15^\circ$ can also resonate with TL₁ at the third harmonic and its physical size is shorter, TL₂ with electrical length of $75^\circ$ has been employed because of its wider tuning space for characteristic impedance $Z_2$, so as to compensate $C_x$ at $5\omega_0$ as far as possible.

Finally, at $\omega_0$, an output match network (OMN) is created in order to compensate $C_x$ and match the $50\Omega$ load to optimal load reactance like (1).

4 Design and verification

A design example of the class-E/F₃ PA with TLCC is presented in order to better understand the theoretical analysis described in the previous sections.

The design objectives are set as follows: $V_{DS} = 28$ V and $P_{out} = 10$ W. The transistor used in implementation is a CGH40010F GaN HEMT from Wolfspeed with $C_{out} = 1.2$ pF. Substituting these values into (6) yields $f_{max} = 0.54$ GHz. According to (5), if the operation frequency is increased to 2.14 GHz, whose $f_{max}$
is 4 times larger than that of the conventional circuit, the value of the shunt capacitance $C$ is decreased to 0.3 pF. Since $C_{out} = 1.2$ pF, the excess capacitance $C_x$ required is 0.9 pF, implying $K = 3$. Based on the theoretical analysis in the previous section, the schematic of TLCC for class-E/F$_3$ is presented in Fig. 3. The proposed class-E/F$_3$ PA with TLCC contains the loading network, input matching network (IMN), biasing, and stabilizing circuits. The transmission-line parameters for loading network in Fig. 3 can be calculated by (1)–(4) and (8)–(11). Here, the simulated load impedances for the fundamental and harmonics are plotted in Fig. 4. In accordance with (1), the class-E/F$_3$ PA mode requirements for short-circuit and open-circuit terminations at harmonics ($2\omega_0$, $3\omega_0$, $4\omega_0$) are met concurrently, as is the optimal impedance at $\omega_0$. Furthermore, by tuning the characteristic impedance $Z_2$, the impedance of the fifth harmonic is adjusted as high as possible. Therefore, the proposed TLCC can effectively compensate the excess output capacitance $C_x$ at both the fundamental and harmonic frequencies.

![Fig. 3. Circuit schematic of the proposed TLCC for Class-E/F$_3$.](image)

![Fig. 4. Simulated load impedances of the TLCC for class-E/F$_3$ PA at fundamental and harmonic frequencies.](image)

For a practical transistor, the parasitic network formed by bonding wires and package lead does not match the required exact values of proposed class-E/F$_3$ PA with TLCC in Fig. 3. Hence, the loading network is slightly modified by optimizing the parameters of the series and shunt transmission-lines. A 28 Ω resistor connected in parallel with a 3.9 pF capacitance is used to make the PA stable.
Furthermore, the input matching network provides the optimum input impedance of
the transistor, obtained by the source-pull simulation, to a 50 \( \Omega \) source.

The final photograph of the proposed class-E/F3 PA with TLCC is illustrated in
Fig. 5. The circuit is fabricated on Rogers 5880 substrate with a thickness of 31 mil
and dielectric permittivity of 2.2. The total size of the module is 8.2 cm \( \times \) 5.8 cm.
The active device is biased with a drain voltage of 28 V, gate bias voltage of \(-3 \) V
and drain quiescent current of 68.1 mA.

![Photograph of the fabricated class-E/F3 PA with TLCC.](image)

**Fig. 5.** Photograph of the fabricated class-E/F3 PA with TLCC.

![Simulated and measured output power, gain, DE and PAE versus RF input power.](image)

**Fig. 6.** Simulated and measured output power, gain, DE and PAE versus RF input power on the condition that \( f_0 = 2.14 \) GHz, \( V_G = -3 \) V, \( V_D = 28 \) V.

The proposed class-E/F3 PA with TLCC is characterized under different driving
powers to evaluate its dynamic performance. The measured and simulated results
for output power, gain, drain efficiency (DE) and power-added efficiency (PAE)
versus RF input power are illustrated in Fig. 6. As shown in Fig. 6, The perform-
ance of a peak PAE of 78.0% and DE of 82.9% is obtained at an output power of 40.3 dBm.

Fig. 7 shows the measured PA performance of output power, gain, DE and PAE from 1.9 GHz to 2.4 GHz with a constant input power of 30 dBm. A DE of larger than 60% can be maintained from 2.0 to 2.36 GHz.

As summarized in Table I, a performance comparison of the recently reported high-efficiency microwave PAs is presented. A frequency-weighted average efficiency (FE) is introduced here to evaluate the PA efficiency together with frequency

<table>
<thead>
<tr>
<th>Ref.</th>
<th>Class</th>
<th>$f_0$ (GHz)</th>
<th>$\eta$ (%)</th>
<th>PAE (%)</th>
<th>Gain (dB)</th>
<th>$P_{out,sat}$ (dBm)</th>
<th>FE$^2$ (%)</th>
</tr>
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<tr>
<td>[10]</td>
<td>E/F3</td>
<td>2.14</td>
<td>76.0</td>
<td>73.1</td>
<td>14.3</td>
<td>40.0</td>
<td>88.4</td>
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<td>[17]</td>
<td>PC$^1$E</td>
<td>2.80</td>
<td>76.0</td>
<td>70.8</td>
<td>10.7</td>
<td>40.1</td>
<td>91.6</td>
</tr>
<tr>
<td>[18]</td>
<td>E</td>
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<td>73.7</td>
<td>70.0</td>
<td>12.0</td>
<td>43.0</td>
<td>84.7</td>
</tr>
<tr>
<td>[19]</td>
<td>E</td>
<td>2.90</td>
<td>77.5</td>
<td>72.2</td>
<td>12.2</td>
<td>40.2</td>
<td>94.2</td>
</tr>
<tr>
<td>[20]</td>
<td>E</td>
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<td>63.4</td>
<td>-</td>
<td>-</td>
<td>84.1</td>
</tr>
<tr>
<td>[21]</td>
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<td>19.0</td>
<td>41.0</td>
<td>78.8</td>
</tr>
<tr>
<td>[22]</td>
<td>F</td>
<td>2.40</td>
<td>82.2</td>
<td>74.0</td>
<td>10.0</td>
<td>20.0</td>
<td>92.1</td>
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<tr>
<td>[23]</td>
<td>F</td>
<td>1.88</td>
<td>75.8</td>
<td>70.7</td>
<td>11.7</td>
<td>39.7</td>
<td>82.8</td>
</tr>
<tr>
<td>[24]</td>
<td>F$^{-1}$</td>
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<td>83.1</td>
<td>81.3</td>
<td>15.9</td>
<td>39.7</td>
<td>81.3</td>
</tr>
<tr>
<td>[25]</td>
<td>F$^{-1}$</td>
<td>2.35</td>
<td>-</td>
<td>63.8</td>
<td>-</td>
<td>32.2</td>
<td>79.0</td>
</tr>
<tr>
<td>[26]</td>
<td>EF</td>
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<td>85.0</td>
<td>81.0</td>
<td>13.1</td>
<td>41.9</td>
<td>89.6</td>
</tr>
<tr>
<td>[27]</td>
<td>EF$^3$</td>
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<td>-</td>
<td>63.4</td>
<td>-</td>
<td>-</td>
<td>83.4</td>
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<tr>
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<td><strong>2.14</strong></td>
<td><strong>82.9</strong></td>
<td><strong>78.0</strong></td>
<td><strong>12.3</strong></td>
<td><strong>40.3</strong></td>
<td><strong>94.3</strong></td>
</tr>
</tbody>
</table>

1PC: parallel circuit.
2FE: frequency weighted efficiency (GHz)$^{0.25}$*PAE.
It is evident that the proposed PA products the highest FE among the mentioned PAs because of its extended operating frequency and high efficiency.

5 Conclusion

In this paper, a transmission-line compensation circuit has been developed in order to compensate the excess output capacitance and consequently extend the maximum operating frequency $f_{\text{max}}$ of a class-E/F$_3$ PA mode when keeping its optimal mode of operation. Theoretical analysis has been presented so as to determine the values of the required circuit elements in detail. Based on the methodology developed in this paper, the proposed class-E/F$_3$ PA has been designed, fabricated, and measured. The high-performance results of the fabricated class-E/F$_3$ PA have been realized with the output power of 40.3 dBm, drain efficiency of 82.9% at the operating frequency of 2.14 GHz. In brief, due to its extended $f_{\text{max}}$, simple construction and high performance, the class-E/F$_3$ PA with TLCC is suitable for use as a high efficiency PA operating in the microwave band.

Acknowledgments

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