A 1.5GHz GaN HEMT Fifth-Harmonic-Peaking Class-EF Power Amplifier with 85% Drain Efficiency and 42dBm Output Power

A 1.5 GHz GaN HEMT Fifth-Harmonic-Peaking Class-EF Power Amplifier with 85% Drain Efficiency and 42 dBm Output Power

Mury Thian, Ayman Barakat, and Vincent Fusco

ECIT Institute, The Queen’s University of Belfast, United Kingdom

Abstract — In this paper, we present the design and implementation of a new variant of Class-EF PA, the so-called fifth-harmonic-peaking Class-EF. It inherits soft-switching operation from the Class-E PA and low peak switch voltage from the Class-F PA. The new topology also allows operations at higher frequencies and permits deployment of large transistors. Further, by employing novel \( \lambda/8 \) open and shorted stub arrangements, the PA is able to facilitate better even harmonic suppression leading to improved PA efficiency. Measured peak drain efficiency of 85% and output power of 42 dBm were obtained at 1.5 GHz. Across a 300 MHz frequency range i.e. 20% bandwidth, the PA delivered output power >40 dBm with drain efficiency >65%.

Index Terms — Class-E, Class-EF, Class-F, fifth-harmonic-peaking, GaN, HEMT, power amplifier, transmission line.

I. INTRODUCTION

The Class-EF PA recently introduced in [1]-[2], Fig. 1(a), offers a low peak switch voltage of \( 2 \times V_{DC} \) as in the Class-F as well as soft-switching operation as in the Class-E. However, the total series inductance \( L + L_0 \) associated with this type of circuit is typically of large value and is normally accompanied with large electrical series resistance (ESR) which leads to efficiency degradation. In addition, large inductance results in low self-resonance frequency which restricts high-frequency implementation. Another major challenge in Class-EF PA design is that for a given output power and DC supply voltage, the maximum operating frequency (\( f_{MAX} \)) is constrained by the transistor output capacitance, \( C_{OUT} \), i.e., at high frequencies the value of \( C_{OUT} \) is typically larger than the value of \( C \), Fig.1(a), resulting from the Class-EF synthesis. The fact that large devices with high-power-handling capability are always accompanied with high \( C_{OUT} \) would render the Class-EF PA topology unsuitable for high power applications.

In order to address all of the above issues, a new variant of Class-EF PA, namely fifth-harmonic-peaking Class-EF PA, was proposed in [3], in which the circuit’s theoretical analysis was verified through simulations using an ideal switch model. In this paper, we present the design, implementation and characterization of this type of PA using a high-power GaN HEMT, Fig. 1(b). Here, the \( \lambda/4 \) transmission line (TL) employed in [3] is replaced with a \( \lambda/8 \) open and shorted stub arrangement of novel topology which offers better open and short circuit terminations at the transistor’s drain, and hence improves PA efficiency. In addition, the transmission-line load network is designed not only to satisfy the Class-EF impedances at the fundamental frequency, 3rd and 5th harmonic, and all even harmonics but also to simultaneously provide impedance matching to the PA 50Ω load thus obviating additional output matching circuitry.

II. OPTIMUM IMPEDANCES OF CLASS-EF PA

The circuit schematic of the Class-EF PA with lumped-element load network is illustrated in Fig. 1(a). The series resonator \( L_0 - C_0 \) is tuned to \( f_0 \) and as a result the load network will present \( R \) in series with \( L \) at \( f_0 \) and an open circuit at higher harmonics. The \( \lambda/4 \) TL connected at the drain takes the role of enforcing a short-circuit termination at even harmonics. The
Fig. 3. Complete circuit schematic including input matching network, biasing and stabilizing circuits.

optimum load impedances, \(Z_{OPT}\), seen by the device at \(f_0\) and higher harmonics are described in (1). For prescribed output power \((P_O)\), DC supply voltage \((V_{DC})\), and operating frequency \((f_0)\), the optimum values of \(R\), \(L\), and \(C\) can be calculated using (2)-(4), [2]. The relationship between the parameter \(\tau_0\) in (2)-(4) and duty ratio \(D\) is given by \(D = 0.5 - \tau_0/(2\pi)\). For example, \(\tau_0 = \pi/2\) corresponds to \(D = 0.25\) meaning that the transistor will be switched on only for a 25% period of full cycle.

\[
Z_{OPT} = \begin{cases} 
R + j\omega L & \text{at } f_0 \\
0 & \text{at } 2nf_0, \ n = 1,2,3,\ldots \\
\infty & \text{at } (2n+1)f_0, \ n = 1,2,3,\ldots 
\end{cases} \quad (1)
\]

\[
R = \frac{2(1 + \cos \tau_0)}{\pi^2} \cdot \frac{V_{DC}^2}{P_O} \quad (2)
\]

\[
L = \frac{\tau_0 - 0.5 \sin(2\tau_0)}{\sin^2 \tau_0} \cdot \frac{R}{\omega_0} \quad (3)
\]

\[
C = \frac{\pi}{2} \cdot \left( \frac{\sin \tau_0}{1 + \cos \tau_0} \right)^2 \cdot \frac{P_O}{\omega_0^2 V_{DC}} \quad (4)
\]

III. FIFTH-HARMONIC-PEAKING CLASS-EF PA

In reality it is impossible to realize a transmission-line load network that would simultaneously satisfy Class-EF impedance requirements at the fundamental frequency as well as at all even and odd harmonics (1) since that would require an infinite number of transmission lines. However a good approximation to the idealized Class-EF operation can be achieved by satisfying the required impedances at \(f_0\), all even harmonics, and only the first few odd harmonics. In [3] a fifth-harmonic-peakng Class-EF PA was proposed with the open-circuit requirement satisfied only at \(3f_0\) and \(5f_0\). An extra capacitance \(C_X\) was added to the circuit and as a result the device output capacitance \(C_{OUT}\) now increases to \(C + C_X\), which translates into higher \(f_{MAX}\). Note that \(C_X\) in Fig. 1(b) is a DC blocking capacitance.

At \(f_0\) TL1 – TL6 together with \(C_X\) will transform the load resistance \(R_i\) into \(R + j\omega_0 L\). At \(3f_0\), the open stub TL2 has a capacitive reactance whereas the shorted stub TL3 has an inductive reactance. These capacitive and inductive reactances are designed to resonate at \(3f_0\) and therefore behave like an open circuit. As a consequence TL4 and TL5 are now in series connection. Meanwhile the right-hand end of TL4 will be shorted by TL4. TL3 together with shorted TL4 behave like an inductance and are designed to resonate with \(C_X\) at \(3f_0\), hence facilitating an open circuit. At \(5f_0\), the right-hand end of TL4 will be shorted by TL2. This shorted TL1 which acts like an inductance is designed to resonate with \(C_X\) at \(5f_0\) so as to provide the required Class-EF odd-harmonic open-circuit condition. TL6 takes the role of suppressing the 7th harmonic.

The \(\lambda/8\) open and shorted stubs depicted in Fig. 1(b) replace the traditional \(\lambda/4\) line deployed in Fig. 1(a), [3]. The \(\lambda/8\) open stub will short circuit the drain of the transistor at \((4m-2)\)th harmonics whereas the \(\lambda/8\) shorted stub will short circuit the drain of the transistor at \((4m)\)th harmonics whereas \(m = 1, 2, 3\), etc. Together they will facilitate a short-circuit termination at all even harmonics. At \(f_0\) the \(\lambda/8\) shorted stub behaves like an inductance \(L_1\) (5) while the \(\lambda/8\) open stub behaves like a capacitance \(C_8\) (6). This parallel \(L_1 - C_8\) circuit is designed to resonate at \(f_0\) (7).

\[
j\omega L = jZ, \quad \tan 45^\circ = jZ, \quad \omega_0 C = jY, \quad \tan 45^\circ = jY, \quad \omega_0 L, C = 1 \quad (5) - (6) - (7)
\]

Substitution of (5)-(6) into (7) results in \(Z_8 = Z_0\). By setting \(Z_8\) equal to \(Z_0\) the proposed stub arrangement provides an open circuit not only at \(f_0\) but also at all odd harmonics. The characteristics of the \(\lambda/8\) open and shorted stubs at \(f_0\) and higher harmonics are compared with the \(\lambda/4\) TL in Fig. 2. It can be observed that the proposed arrangement offers 100% wider rejection band (IS211 \(\leq -10\) dB) than the \(\lambda/4\) TL.

IV. FABRICATION AND MEASUREMENT RESULTS

The circuit schematic of the fifth-harmonic-peakng Class-EF PA is shown in Fig. 3. The circuit component values, also given Fig. 3, were calculated using design equations above with little tuning involved during the optimization to cancel the effect of the microstrip-cross-junction components. It employs a simple L-type input matching network comprised of a series capacitance 1.8 pF and a 6.05mm long shorted stub. The PA employs a packaged GaN HEMT CGH40010F from CREE with high drain-source breakdown voltage of 120V. The transistor is potentially unstable at frequencies below 3.5
GHz and a series resistance of 5 Ω was added at the gate to prevent oscillations particularly at around 500 MHz. The PA was realized on a 20-mil thick Rogers RO4003C substrate with dielectric constant of 3.55, loss tangent of 0.0027, and thermal conductivity of 0.71 W/m/°K. The photograph of the PA prototype measures 4 × 4 cm$^2$ is shown in Fig. 4.

Measured PA performances in terms of output power, gain, drain efficiency and PAE at $V_{DC} = 32$ V and $V_{GS} = -2.8$ V are plotted against frequency in Fig. 5. Across a 300 MHz frequency range from 1.42 to 1.72 GHz, the PA delivered output power >40 dBm with drain efficiency >65% and PAE >62%. Plotted in Fig. 6 are the measured PA performances versus input power at 1.52 GHz. Peak drain efficiency of 85% and peak PAE of 81% were achieved at 42 dBm output power and 13.1 dB gain. The linear gain is about 16 dB. Fig. 7 shows the PA’s behavior when the drain voltage is varied. Drain efficiency of at least 75% was achieved when the $V_{DC}$ was varied from 14 to 32 V. The PA performances are summarized in Table I and compared with other GaN PAs.

V. CONCLUSIONS

A fifth-harmonic-peaking Class-EF PA employing novel $\lambda/8$ open and shorted stubs which facilitate improved even harmonic suppression and therefore offer higher efficiency has been designed, fabricated and characterized. At 1.5 GHz, the PA delivered 42 dBm output power with 85% drain efficiency. Drain efficiency of at least 75% was achieved under 14-32V $V_{DC}$ variation suggesting that the PA would be useful for insertion in systems where the input signal is to be modulated through the drain of the PA.

### Table I

<table>
<thead>
<tr>
<th>Ref</th>
<th>Freq (GHz)</th>
<th>$P_{out}$ (dBm)</th>
<th>$\eta$ (%)</th>
<th>PAE (%)</th>
<th>Gain (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>[4]</td>
<td>1.0</td>
<td>37</td>
<td>78.8</td>
<td>77.7</td>
<td>13.7</td>
</tr>
<tr>
<td>[5]</td>
<td>1.0</td>
<td>39.8</td>
<td>77.5</td>
<td>74.2</td>
<td>13.7</td>
</tr>
<tr>
<td>[6]</td>
<td>2.14</td>
<td>37</td>
<td>73</td>
<td>70</td>
<td>15</td>
</tr>
<tr>
<td>[7]</td>
<td>2.22</td>
<td>39.2</td>
<td>80.5</td>
<td>71</td>
<td>9.3</td>
</tr>
<tr>
<td>This work</td>
<td>1.5</td>
<td>42</td>
<td>85</td>
<td>81</td>
<td>13.1</td>
</tr>
</tbody>
</table>

### REFERENCES