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Analysis and Design of a High-Efficiency Class-EM Power Amplifier

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Abstract — The Class-EM power amplifier (PA) offers the possibility of achieving high-efficiency operations at high operating frequencies while using slow-switching transistors. This is made possible by the adoption of the ZVS/ZVDS/ZCS and ZCDS conditions on the main circuit and the adoption of the ZVS condition on the auxiliary circuit. In this paper, we present the analysis and design of a new topology of the Class-EM PA incorporating a finite DC-feed inductance and an isolation circuit, rendering it more attractive for implementations. Furthermore, we propose a novel transmission-line load network that provides the drain of the transistor with the required load impedances at the fundamental frequency as well as at even and odd harmonic frequencies for the main and the auxiliary circuits. The concept is verified through harmonic-balance simulations with the PA exhibiting a peak drain efficiency of 90.3%, a peak power added efficiency of 86.7%, and a peak output power of 41.2 dBm at an operating frequency of 1.5 GHz.

Index Terms — Class-EM, DC-feed inductance, GaN, harmonic tuning, high-efficiency, switching power amplifier, transmission-line, ZCS, ZCDS, ZVS, ZVDS.

I. INTRODUCTION

The Class-EM power amplifier (PA) introduced in [1], delivers a theoretical efficiency of 100% through adoption of slow voltage switching (ZVS), zero voltage derivative switching (ZVDS), zero current switching (ZCS) and zero current derivative switching (ZCDS) conditions on the main circuit, and ZVS condition on the auxiliary circuit. By satisfying both ZVS/ZVDS and ZCS/ZCDS conditions, it minimizes the power dissipation within the switch during not only OFF-to-ON transition (as in the classical Class-E) but also ON-to-OFF transition. As a result, slow-switching (low cost) transistors can be used to perform high-efficiency amplification at high frequencies.

However, it was shown in [2] that some of the core design equations presented in [1] are incorrect and ambiguous while the analyses in [3]-[4] result in a large system of nonlinear equations whose solutions offer little insights into how the circuit operates, thus hampering the widespread usage thereof. Although the simplified and accurate analysis presented in [2] results in explicit design equations, the optimum fundamental-frequency load impedance \( Z_{\text{opt}}(f_0) \) presented to the main switch is capacitive. This poses a major problem in the implementation since many commercially available power devices require inductive loading at the fundamental frequency \( f_0 \) in order to achieve high-efficiency operations.

The circuits analysed in [1]-[4] employ ideal RF chokes. In this paper, we propose a new Class-EM PA topology which employs a finite DC-feed inductance and an isolation circuit. The isolation circuit enables the main and auxiliary circuits to be analysed separately, thereby significantly simplifying the highly sophisticated analyses presented in [3]-[4]. The use of a finite DC-feed offers some practical advantages, such as reduced size and improved performance due to reduced parasitic series resistance.

More importantly, we introduce a new design parameter \( k \), which allows \( Z_{\text{opt}}(f_0) \) to be either inductive or capacitive, thus offering a design flexibility and rendering the Class-EM PA more practically attractive. The parameter \( k \) can also be exploited to reduce the voltage peak factor of the main switch, which is 4.27 as in [1]-[4], and which is higher than that of the classical Class-E.

Furthermore, the Class-EM PAs in [1] and [3]-[4] were implemented at low operating frequencies (below 15 MHz), shying away from demonstrating the true benefit of the Class-EM PA soft-switching capability. To highlight this capability, we designed a GaN HEMT Class-EM PA operating at 1.5 GHz using a novel transmission-line load network. To reduce the voltage peak factor of the main switch the proposed transmission-line load network adopts the Class-F\-1 harmonic terminations, paving the way for the first practical design of a transmission-line Class-EM PA at RF frequencies.

II. CIRCUIT ANALYSIS

The proposed Class-EM PA configuration, shown in Fig. 1, is comprised of a main circuit, an auxiliary circuit and an isolation circuit. The main and auxiliary circuits each consisting of shunt capacitances \( C_{S1}, C_{S2} \), finite DC-feed inductances \( L_{C1}, L_{C2} \), a series resonant circuit \( L_{C1} \) tuned at \( f_0 \), \( L_{C2} \) tuned at \( 2f_0 \), and series reactances \( X_{L1}, X_{L2} \).
The purpose of the auxiliary circuit and the working principle of the isolation circuit are explained in [2].

The optimum Class-Em switching conditions are given in (1)-(3). The load current \(i_R(\theta)\) and the injected current \(i_{inj}(\theta)\) are given in (4), where \(\theta = \omega t\) (rad), \(I_R\) and \(\alpha\) are the amplitude and phase shift of the \(f_0\) load current, \(I_{inj}\) and \(\beta\) are the amplitude and phase shift of the \(2f_0\) injected current.

\[
\begin{align*}
v_{s1}(\theta)|_{\theta=2\pi} &= 0; \quad \frac{dv_{s1}(\theta)}{d\theta}|_{\theta=2\pi} = 0 \quad (1) \\
i_{s1}(\theta)|_{\theta=\pi} &= 0; \quad \frac{di_{s1}(\theta)}{d\theta}|_{\theta=\pi} = 0 \quad (2) \\
v_{s2}(\theta)|_{\theta=\pi} &= 0 \quad (3) \\
i_R(\theta) &= I_R \sin(\theta + \alpha); \quad i_{inj}(\theta) = I_{inj} \sin(2\theta + \beta) \quad (4)
\end{align*}
\]

During the ON period, the current \(i_{s1}(\theta)\) is given in (5) flows through \(S_1\) of Fig. 2(a), where \(m\) and \(p\) are defined in (6), and the voltage across \(S_1\), \(v_{s1}(\theta)\) is \(0\).

\[
i_{s1}'(\theta) = \frac{\omega L_i C_1}{V_{dc1}} i_{s1}(\theta) = \theta + p [\sin(\theta + \alpha) - \sin(\alpha)] + m [\sin(2\theta + \beta) - \sin(\beta)] \quad (5) \\
m = \frac{\omega L_i C_1}{V_{dc1}}; \quad p = \frac{\omega L_i C_1}{V_{dc1}} \quad (6)
\]

During the OFF period, \(i_{s1}(\theta) = 0\) and \(v_{s1}(\theta)\) is given in (7), where \(k_1\) is defined in (8) and the coefficients \(C_1\) and \(C_2\) can be obtained by applying the initial OFF conditions to (7). Applying the conditions in (1)-(2) to (5) and (7) results in a set of four equations with four unknown parameters \(m\), \(p\), \(\alpha\), and \(\beta\), whose solutions are given in terms of \(k_1\).

\[
v_{s1}(\theta) = C_1 \cos(k_1 \theta) + C_2 \sin(k_1 \theta) + 1 - \frac{2\alpha k_1 m}{1-k_1^2} \cos(2\theta + \beta) \quad (7) \\
k_1 = \frac{1}{\omega L_i C_1} \quad (8)
\]

The load network parameters of the main circuit given in (9)-(10) are obtained by applying the condition for maximum drain efficiency \((DE)\) in a Class-Em PA, derived in [2] and using Fourier series expansion of \(v_{s1}(\theta)\). Subsequently, \(I_{inj}\) is given in (10).

\[
R_{opt} = \frac{V_D^2}{2P_{out}}; \quad \omega L_{C1} = \frac{p V_{DC1} V_{DC1}}{2P_{out}}; \quad \alpha = \frac{1}{k_1^2} \quad (9) \\
x_1 = \frac{v_{x1}^2}{2P_{out}}; \quad I_{inj} = \frac{2m P_{out}}{k_1^2} \quad (10)
\]

During the ON period, the current \(i_{s2}(\theta)\) is given in (11) flows through \(S_2\) of Fig. 2(b), where \(r\) is defined in (12), and the voltage across \(S_2\), \(v_{s2}(\theta)\) is \(0\).

\[
i_{s2}'(\theta) = \frac{\omega L_i C_2}{V_{dc2}} i_{s2}(\theta) = \theta - r [\sin(2\theta + \beta) - \sin(\beta)] \quad (11) \\
r = \frac{\omega L_i C_2 I_{inj}}{V_{dc2}} \quad (12)
\]

During the OFF period, \(i_{s2}(\theta) = 0\), and \(v_{s2}(\theta)\) is given in (13), where \(k_2\) is defined in (14) and the coefficients \(C_1\) and \(C_2\) can be obtained by applying the initial OFF conditions to (13). Applying the condition in (3) to (13) results in a single equation with an unknown parameter \(r\), whose solution is given in terms of \(k_2\).

\[
v_{s2}(\theta) = C_3 \cos(k_2 \theta) + C_4 \sin(k_2 \theta) + 1 - \frac{2k_2^2 r \cos(2\theta + \beta)}{k_2^2 - 4} \quad (13) \\
k_2 = \frac{1}{\omega \sqrt{V_{dc2}} \cos(2\theta + \beta)} \quad (14)
\]

The load network parameters of the auxiliary circuit given in (15) are obtained using Fourier series expansion of \(v_{s1}(\theta)\) and \(v_{s2}(\theta)\) and by applying KVL to the circuit in Fig. 2(b).

\[
\omega L_{C2} = \frac{r V_{DC2}}{I_{inj}}; \quad \omega C_{2} = \frac{1}{k_2^2 \omega C_{2}}; \quad x_2 = \frac{V_{DC1} + V_{DC2}}{I_{inj}} \quad (15)
\]

It was shown in [2] that the DC power of the auxiliary circuit \((P_{DC2})\) is one-third of the DC power of the main circuit \((P_{DC1})\), and consequently, \(I_{DC1}\) and \(I_{DC2}\) can be used to determine the required DC supply voltage of the auxiliary circuit \(V_{DC2}\) for a prescribed \(V_{DC1}\), where \(I_{DC1}\) and \(I_{DC2}\) are the average values of \(i_{s1}(\theta)\) and \(i_{s2}(\theta)\) respectively.

III. DESIGN EXAMPLE AND VERIFICATION

The Class-Em PA in Fig. 1 was designed and simulated in ADS with a specified \(V_{DC1} = 28\) V and \(f_0 = 1.5\) GHz. The parameters \(m = 0.21\), \(p = -1.69\), \(\alpha = 60.9\) rad, \(\beta = 22.37\) rad and \(r = 0.51\) were obtained for \(k_1 = 2.8\). The DC currents \(I_{DC1}\) and \(I_{DC2}\) were obtained as 234 mA and 184 mA respectively. Using condition (11) from [2], \(P_{DC1} = 6.55\) W and \(P_{out} = 8.74\) W were obtained. The load network parameters of the main circuit are determined using (9)-(10): \(R_{opt} = 6.1\) \(\Omega\), \(L_{C1} = 2.97\) nH, \(C_{1} = 0.43\) pF, and \(C_{2} = 3.74\) pF.

The required DC voltage of the auxiliary circuit is \(V_{DC2} = 0.42 \times V_{DC1} = 11.9\) V and the load network parameters of the auxiliary circuit are determined using (10) and (15) as: \(L_{C2} = 3.1\) nH, \(C_{2} = 0.47\) pF, \(C_{2} = 0.4\) pF. Here, the characteristic impedance of TLs and TL-10 of the isolation circuit is set to 80 \(\Omega\).

The idealized simulated results depicted in Fig. 3(a) and Fig. 3(b), show that the main circuit fulfills the ZVS/ZVS/ZCS and ZCDS conditions with a peak switch current of 3.37×\(I_{DC1}\) and voltage of 4.49×\(V_{DC1}\), while the
Fig. 3. Normalized switch voltage and current waveforms: (a) main circuit, (b) auxiliary circuit.

The auxiliary circuit fulfills the ZVS condition with a peak switch current of $2.65 \times I_{DC2}$ and voltage of $3.7 \times V_{DC2}$. These results agree well with the theoretical predictions.

IV. PROPOSED PA WITH TL LOAD NETWORK

The proposed PA with transmission-line (TL) load network is depicted in Fig. 4 with the main circuit operated at $f_0$ and the auxiliary circuit operated at $2f_0$. To reduce the peak drain voltage of the original Class-EM PA, the load network of the main circuit is designed to satisfy the Class-F-1 harmonic terminations, namely open circuit at $2f_0$ and short circuit at $3f_0$, which can be achieved through the following arrangement. A series $\lambda/8$ line (TL1) is short-circuited at its right-hand side by an open-circuited $\lambda/8$ stub (TL2B), hence $Z_{inM}(2f_0) = \infty \Omega$. TL2B together with a shorted $\lambda/8$ stub (TL2A) enforce an open-circuit termination at $f_0$ and odd harmonic frequencies with $Z_2$ set to a high value [5]. Thus, the combined series lines TL1 and TL3 with a total electrical length of $\lambda/6$ (i.e. $\lambda/8 + \lambda/24$) short-circuited at its right-hand side by an open-circuited $\lambda/12$ stub (TL4A) provides a short circuit at $3f_0$, hence $Z_{inM}(3f_0) = 0 \Omega$. The characteristic impedances of TL1/TL3 and TL4A/TL4B, i.e. $Z_1 = Z_3$ and $Z_4$ are calculated to match the optimum load impedance $Z_{opt}(f_0)$ to the standard 50 $\Omega$ load resistance ($R_L$).

A series transmission-line (TL5) with an electrical length $\theta_5$ and characteristic impedance $Z_5$ is used to absorb the lead inductance of the auxiliary transistor. A shorted $\lambda/16$ (TL6A) in conjunction with an open-circuited $\lambda/16$ (TL6B) enforce short-circuit terminations at even harmonic frequencies, and open-circuit terminations at fundamental and odd harmonic frequencies with $Z_6$ set to a high value [5], hence $Z_{inA} = 0 \Omega$ at $4f_0$. The series $\lambda/12$ (TL7) together with the open-circuited $\lambda/24$ stub (TL8), enforce a short-circuit termination at $6f_0$, hence $Z_{inA} = 0 \Omega$ at $6f_0$.

A PA prototype was designed at 1.5 GHz using two Cree CGH40010F GaN HEMTs. The main and auxiliary circuits were biased with $V_{DC1} = 28$ V, $V_{GG1} = -2.7$ V and $V_{DC2} = 14$ V, and $V_{GG2} = -2.8$ V. $Z_{opt}(f_0)$ and $Z_{opt}(2f_0)$ were extracted from load-pull simulations on the main circuit at $f_0$ and $2f_0$ while sweeping the injected power. $Z_{opt}(2f_0)$ was extracted from load-pull simulations on the auxiliary circuit at $2f_0$. The characteristic impedances $Z_1 = Z_3$ and $Z_4$ were calculated to match $Z_{opt}(f_0)$ to 50 $\Omega$ while $Z_1$ and $Z_8$ were calculated to match $Z_{opt}(2f_0)$ to $Z_{opt}(2f_0)$. The PA was then implemented with microstrip lines on a 0.51 mm thick Rogers RO4003C substrate.

Fig. 4. Proposed PA with TL novel load network.

The characteristic impedances of TL1, TL3, TL4A and TL4B, i.e. $Z_1 = Z_3$ and $Z_4$ are calculated to match the optimum load impedance $Z_{opt}(f_0)$ to the standard 50 $\Omega$ load resistance ($R_L$).

A series transmission-line (TL5) with an electrical length $\theta_5$ and characteristic impedance $Z_5$ is used to absorb the lead inductance of the auxiliary transistor. A shorted $\lambda/16$ (TL6A) in conjunction with an open-circuited $\lambda/16$ (TL6B) enforce short-circuit terminations at even harmonic frequencies, and open-circuit terminations at fundamental and odd harmonic frequencies with $Z_6$ set to a high value [5], hence $Z_{inA} = 0 \Omega$ at $4f_0$. The series $\lambda/12$ (TL7) together with the open-circuited $\lambda/24$ stub (TL8), enforce a short-circuit termination at $6f_0$, hence $Z_{inA} = 0 \Omega$ at $6f_0$.

Fig. 5. Simulated drain voltage and current waveforms (a) main circuit, (b) auxiliary circuit.
The simulated drain voltage and current waveforms of the main and auxiliary circuits at an input power $P_{in} = 27$ dBm are depicted in Fig. 5(a) and Fig. 5(b) showing that the main circuit fulfills the ZVS/ZVDS/ZCS/ZCDS conditions while the auxiliary circuit fulfills the ZVS condition, thus demonstrating the soft-switching capability of the Class-EM PA. The drain voltage peak factor of the main circuit is decreased to 3.28 as a result of adopting the Class-F-1 harmonic terminations.

The simulated PA performance, depicted in Fig. 6, shows that at $P_{in} = 27$ dBm, the PA delivers a $DE$ of 89 %, a $PAE$ of 86.7 %, a $P_{out}$ of 41.25 dBm, and a gain of 14.2 dB at a $f_0$ of 1.5 GHz. Fig 7 shows the simulated output power spectrum with excellent harmonic suppression levels of more than 43 dBC up to the sixth harmonic, showing the effectiveness of the proposed transmission-line load network. The simulations also showed that $P_{DC2}$ is approximately one-third of $P_{DC1}$ and the auxiliary PA contributes approximately one-quarter of $P_{out}$ which is aligned with the theory in [2].

IV. CONCLUSION

The analysis and design of a high-efficiency Class-EM PA has been presented, the accuracy of which was verified with ADS harmonic balance simulations of an idealized and practical Class-EM PA. This Class-EM PA fulfills the ZVS/ZVDS/ZCS/ZCDS conditions on the main PA and the ZVS condition on the auxiliary PA, resulting in soft-switching during OFF-to-ON and ON-to-OFF transitions. Thus, the possibility of achieving high-efficiency operation at high operating frequencies with slow-switching devices is demonstrated.

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