Nonlinear Embedding Model-Based Continuous Class E/F Power Amplifier

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Abstract—This letter presents the design of a continuous class E/F power amplifier (PA) using model-based nonlinear embedding. The theoretically calculated continuous class E/F loads defined at the current source reference plane (CRP) may not guarantee feasible loads at the extrinsic package reference plane (ERP) due to nonlinear parasitic. Hence, a design space is analyzed to map the correct mode of the class E/F continuum over broadband to obtain feasible loads. A scheme is presented to assign fundamental current component (φ) to various frequencies over the band to obtain a tradeoff between best bandwidth and feasibility of a passive matching network. A nonlinear embedding model is used to project the loads from CRP to ERP. As a proof of concept, a continuous class E/F PA is designed using CGH27015F. The prototype developed has measured a drain efficiency of 60.2%–76.5% from 1.5 to 2.9 GHz which corresponds to 63.6% fractional bandwidth.

Index Terms—Broadband, continuous class E/F, design space, GaN HEMT, nonlinear embedding model, power amplifier (PA).

I. INTRODUCTION

Several schemes have been proposed in the past to enhance the bandwidth of class E power amplifier (PA) [1]–[4]. Among them, the class E/F continuum has been proposed considering the second-harmonic load (Z2,CRP) in addition to the fundamental load (Z1,CRP) to take care of the zero voltage switching and zero voltage derivative switching conditions [5]. The phase of the fundamental current component (φ) in this continuum varies from 43.3° to 78°. The conventional class E corresponds to φ = 57.5° [5]. Fig. 1(a) shows the voltage and current waveforms of the class E/F continuum. Theoretically, one can map these modes to different frequencies over broadband. However, due to the device parasitic, this mapping may not be as simple as proposed in [5]. Each mode of the class E/F continuum defines different loads at the current source reference plane (CRP). These CRP loads when projected to the extrinsic package reference plane (ERP) may lead to the non-Foster loads based on the device parasitic. Such loads are impractical to match using the passive components which translate to clockwise rotation on the Smith chart with increasing frequency [6], [7]. The CRP refers to the intrinsic switch plane before the shunt capacitor in the conventional class E [3]. This letter presents a new scheme to choose various class E/F continuum modes with the frequency.

This letter presents a unique trend to map φ with the frequency is observed which is quite different from other continuous classes [6], [7]. A tradeoff between bandwidth and feasibility of a passive network is also analyzed. The nonlinear embedding model is used to project loads from CRP to ERP using the embedding transfer network (ETN) which can provide a quick solution while analyzing a design space [8], [9].

II. DESIGN EQUATIONS OF CONTINUOUS CLASS E/F MODE

The class E load network comprises a capacitance C connected in shunt with an ideal switch. Hence, the theoretically calculated loads of the class E/F continuum, when computed along with this C, can give load conditions at the CRP as [5]

$$Z_{1,CRP}(\phi) = \frac{R(1+jx_1)\pi}{\pi + j2(1+jx_1)\cos^2 \phi} \tag{1}$$

$$Z_{2,CRP}(\phi) = \frac{jx_2\pi}{\pi - 4x_2\cos^2 \phi} \tag{2}$$

where

$$R = \frac{(8V_{DD}^2\sin^2 \phi)/(\pi^2 P_{out})}{(3)}$$

$$x_1 = \frac{(16\pi \cos^2 \phi \cot \phi + 2\pi \sin 2\phi + 3\pi^2 - 32)/(12\pi \cos^2 \phi)}{(4)}$$

$$x_2 = \frac{\pi \sec^2 \phi}{24(\pi - 2\tan \phi)} \left[ 4 \sin(2\tan^{-1}(2\cot \phi)) + 3\pi + 2(\cos(2\tan^{-1}(2\cot \phi)) - 2\tan \phi) \right]. \tag{5}$$

These CRP loads, plotted in Fig. 1(b) for φ ∈ [43.3°, 78°], can provide an output power comparable to class E mode. One can see that Z2,CRP is an open circuit for class E/F2 mode (φ = 43.3°) and a short circuit for class EF2 mode (φ = 78°), while...
the intermediate modes require a negative reactance as shown in Fig. 1(a) (blue). The shunt capacitance $C$ can be given as

$$C = (2 \cos^2 \phi) / (\pi \omega R).$$  

(6)

By solving (3) and (6), the expression for $\omega$ can be given as

$$\omega = \pi P_{out} \cot^2 \phi / (4CV^2_{DD}).$$  

(7)

Assuming $\omega = \omega_0$ at $\phi = 57.5^\circ$ (conventional class E) and by normalizing $\omega$ with respect to $\omega_0$, one can write

$$\omega / \omega_0 = f / f_0 = 2.5 \cot^2 \phi.$$  

(8)

Therefore, (8) gives a monotonically decreasing scheme for mapping $\phi$ with the frequency according to the theory proposed in [5] which is illustrated in Fig. 2(a). Section III demonstrates that this assignment may not lead to the Foster loads at ERP when considering real device parasitic.

III. INVESTIGATING DESIGN SPACE WITH NONLINEAR EMBEDDING MODEL

To appropriately design a continuous class E/F PA, the ERP loads must ensure that the device sees the theoretically calculated CRP loads given in (1) and (2). The nonlinear embedding model of a 15-W GaN HEMT Wolfswitch device CGH27015F, as shown in Fig. 2(b), is used to directly project the CRP loads to the ERP using the ETN [8], [9]. The ETN is a multi-port network used to synthesize the multi-harmonic ERP source and load terminations. The nonlinear embedding model is realized with the anticircuit of the device model. This enables the direct access of the CRP and projects loads and waveforms at the ERP [8]. Using the relation (8), $\phi$ is mapped to the frequency, and the CRP loads are projected to the ERP using the nonlinear embedding model, where, $f_0$ is considered as 2.2 GHz. $Z_{1,ERP}$ and $Z_{2,ERP}$ represent the ERP loads at the fundamental and second harmonics, respectively. It can be seen from Fig. 1(a) (gray) that $Z_{2,ERP}$ rotates anticlockwise if $\phi$ is mapped according to (8), which cannot be realized using a passive network. This implies that selection of the frequency and $\phi$ based on (8), as established in theory [5], gives non-Foster loads at the ERP due to the parasitic effects. Therefore, a new assignment scheme must be analyzed to map the CRP loads to the frequencies resulting into the Foster loads at the ERP. Attention has been given to the matching requirement for $Z_{2,ERP}$ as it significantly expands on the Smith chart compared with $Z_{1,ERP}$ for a specified frequency range. Unlike the analysis presented in [6] and [7], the range of design parameter $\phi$ is fixed between $[43.3^\circ$ and $78^\circ]$. Therefore, the entire frequency range is divided into equal intervals and the change in $\phi$ in each of these intervals is considered as $\Delta \phi$. For this analysis, the frequency is divided into equal bins of 100 MHz. Fig. 3(a) and (b) shows the various cases of $\Delta \phi$ and the corresponding $Z_{2,ERP}$, respectively. Unlike the monotonically decreasing $\phi$ shown in Fig. 2(a), increasing $\phi$ with the frequency leads to clockwise rotating $Z_{2,ERP}$ as shown in Fig. 3(b). For example, if $\Delta \phi = -1^\circ$ and $\phi$ is decreased from $69^\circ$ to $55^\circ$ with the frequency, as shown in Fig. 3 (blue), $Z_{2,ERP}$ moves anticlockwise. For $\Delta \phi = 0^\circ$, that is, $\phi$ is set to a constant phase of $62^\circ$ (green), an anticlockwise trend is still observed but with reduced extent giving a clue to consider positive $\Delta \phi$. Moreover, even if $\Delta \phi$ is positive, keeping it fixed may not give optimum bandwidth. A small value of $\Delta \phi$ seems to cover a broadband, but the loads are still non-Foster for several frequencies. One can see from Fig. 3(a) where $\Delta \phi = 2^\circ$ and $\phi$ is increased from $48^\circ$ to $70^\circ$, with the frequency varying from 1.5 to 2.6 GHz, $Z_{2,ERP}$ still moves anticlockwise (pink) in Fig. 3(b) for this case. However, if $\phi$ is further increased from $70^\circ$ to $76^\circ$, with the frequency increasing from 2.6 to 2.9 GHz, $Z_{2,ERP}$ moves clockwise (yellow) as shown in Fig. 3(b) resulting in only the 300-MHz band. Similarly, for a high value of $\Delta \phi$, a full range of $\phi$ [43.3$^\circ$, 78$^\circ$] can only be assigned to limited frequency points resulting in a narrow bandwidth. Fig. 3(a) shows such a case where $\Delta \phi = 5^\circ$ and $\phi$ is increased from $47^\circ$ to $77^\circ$ with the frequency. In this case, $Z_{2,ERP}$ rotates in the clockwise direction as shown in Fig. 3(b) (black) but can only achieve the 600-MHz bandwidth. Thus, keeping $\Delta \phi$ high may result in the Foster loads but with narrow bandwidth. Therefore, a tradeoff exists between high bandwidth and feasible loads at the ERP. The best way is to set $\Delta \phi$ as the variable over the frequency with positive values. Such case is shown in Fig. 3(a) (red) where $\phi$ is varied from $43.3^\circ$ to $76.3^\circ$ with variable $\Delta \phi$ selected over the frequency. The corresponding $Z_{2,ERP}$ rotates clockwise as shown in Fig. 3(b) (red) across the bandwidth of 1.4 GHz. Therefore, to obtain a family of clockwise trajectories of $Z_{ERP}$, $\phi$ is varied in an increasing fashion with the frequency unlike (8). In addition, $\Delta \phi$ is varied in each of the frequency bins as shown in Fig. 3(a) (red). $\Delta \phi$ is kept low in the frequency bins near the lower and upper corners of the frequency range and the value of $\phi$ is assigned as $43.3^\circ$ and $78^\circ$, respectively. Whereas the step size $\Delta \phi$ is increased for the middle frequencies. If $\Delta \phi_i$ is the step size in the $i$th frequency bin, among $n$ equal intervals, the sum of all $\Delta \phi_i$ depends on the range of $\phi$. Therefore, the sum of $\Delta \phi_i$ in each frequency bin ($\sum_i |\Delta \phi_i|$) can take a maximum value of $34.7^\circ$ which is the difference between the upper and lower bounds of $\phi$, that is, $43.3^\circ$ and $78^\circ$. One can write the following relation to obtain feasible loads at the ERP within a broadband as

$$L < \sum_{i=1}^{n} |\Delta \phi_i| \leq 34.7^\circ$$  

(9)
where $L$ is the lower bound of $|\Delta \phi_i|$ which can be defined from the fixed $\Delta \phi$ with the highest bandwidth and feasible loads. Unlike the upper bound of (9), $L$ cannot be uniquely defined and depends on the number of frequency intervals chosen as well as the parametric analysis depending on the device parasitic. In this case, the maximum bandwidth of 600 MHz can be achieved with fixed $\Delta \phi$ corresponding to $\Delta \phi = 5^\circ$. Because the frequency is divided into $n = 6$ intervals of 100 MHz, $L = \sum |\Delta \phi_i| = 33^\circ$. Higher values of $\Delta \phi$ result in a narrow bandwidth. In this letter, $\sum |\Delta \phi_i| = 33^\circ$ has been chosen in designing the prototype described in Section IV. Although the trend of the ERP loads may vary depending on the device parasitic, the strategy holds good. It is worth mentioning that a similar trend is also observed for CGH40010F and CGH40006S devices, whose CRP is accessed using the negative parasitic elements of the device model as proposed by Carrubba [10].

IV. DESIGN IMPLEMENTATION

The schematic of the continuous class E/F PA realized with the 15-W CGH27015F device is shown in Fig. 4. The transistor is unconditionally stabilized and biased with a drain voltage of 28 V and current of 85 mA. Using the presented approach, $Z_{1,CRP}$ and $Z_{2,CRP}$ are selected and projected to the ERP using the ETN [8], [9]. The projected $Z_{2,ERP}$ (red) is synthesized using a passive matching network as shown in Fig. 5(a) (blue). An unequally terminated bandpass filter topology is used to design the input matching network [11].

Fig. 5(b)–(d) shows the simulated CRP waveforms of the designed PA at 1.5, 2.2, and 2.9 GHz, respectively.

V. RESULTS AND DISCUSSION

The continuous class E/F PA is fabricated using Rogers RO4350B with a dielectric constant of 3.66 and thickness of 20 mil. The photograph of the fabricated circuit is shown in Fig. 6(a). The simulated and measured drain efficiency (DE), power added efficiency (PAE), gain, and output power are shown in Fig. 7. The simulated and measured DE varies between 60.2% and 76.5% over the frequency. The PAE in the simulation and measurement varies between 56.5% and 73.8%. The output power varies between 39.4 and 41.9 dBm in the simulation and measurement. The measured gain compression is 2.63–4.19 dB. The circuit is also tested with a two-tone signal with 5-MHz spacing. The measured carrier to the third-order intermodulation suppression ratio (C/IMD3) is better than $-16$ dBc at three frequencies as shown in Fig. 6(b). Hence, the designed continuous class E/F PA operates over the 1.4-GHz band with a fractional bandwidth of 63.6%. Table I presents the summary of the designed continuous class E/F PA and comparison to the state-of-art broadband class E/PAs. The proposed continuous class E/F design methodology provides good performance comparable to the contemporary designs. These state-of-art designs are either broadband class E PAs [1], [2], [4] or broadband class E/F3PAs with reactive compensation [3], while the proposed scheme focuses on the class E/F continuum.

VI. CONCLUSION

The continuous class E/F design space is explored to realize an efficient broadband PA facilitated by the ETN. The behavior of the ERP impedances for different step size and frequencies is studied and a methodology is presented to judiciously select $\phi$ versus frequency yielding realizable matching networks. Based on the presented strategy, broadband and efficient PA has been realized.
REFERENCES


