LETTER

Design of broadband power amplifier based on continuous class-F mode with frequency parameterization

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Abstract This paper investigates the design space of a broadband continuous Class-F power amplifier (PA) at the device package plane. By parameterizing the empirical parameter by frequency, the extrinsic fundamental and second harmonic impedances can be engineered to rotate clockwise on the Smith chart which can be realized by the realistic matching network. The proposed design methodology is verified with the implementation of 10 W PA which operates across 1.7–3 GHz. The experimental results show that this PA can achieve drain efficiency of 54.7%–74.8% in the whole interesting band.

Keywords: broadband, high-efficiency power amplifier, continuous Class-F mode, frequency parameterization, clockwise rotation

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

1. Introduction

Broadband and high efficiency are two key requirements in power amplifier (PA) design for forthcoming wireless communication [1]. To improve efficiency of the PA, several kinds of configurations have been widely used, such as Class-E [2, 3, 4], Class-J [5, 6], Class-F/F⁻¹ [7, 8]. Nevertheless, Class-E and Class-F/F⁻¹ need precise harmonic impedance control which is impractical in broadband application. Class-J amplifier was originally proposed to alleviate this shortcomings. It uses a capacitive harmonic load at the second harmonic rather than a resonant impedance condition. Then, the class-J principle was extended to both the Class-F and inverse Class-F modes in the form of the continuous Class-F [9] and continuous inverse Class-F [10], respectively. To further expand the design space, several hybrid continuous modes and resistive-reactive continuous modes appeared in succession [11, 12, 13, 14, 15, 16, 17, 18, 19]. However, the design space of continuous modes mentioned above is derived at the current generate (I-gen) plane while the matching network is constructed at the package plane [20]. Therefore, the theoretical design space can not provide an intuitive solution for actual PA circuit design. Another problem is the anticlockwise rotation of fundamental and second harmonic impedances at package

plane with the frequency increases [21, 22]. However, all practical matching networks require the impedances to be rotated in a continuous clockwise fashion on the Smith chart across the frequency band [23].

In this paper, a further investigate into the design space of continuous Class-F mode is carried out. By selecting a frequency parameterization for the continuous Class-F mode, practicable impedances can be provided at the device package plane after projection with the typical package equivalent circuit in [24]. Moreover, a 10-W PA operating in the frequency range of 1.7 to 3 GHz with drain efficiency between 54.7%–74.8% is implemented based on these feasible impedances.

2. Review of the continuous Class-F mode

The continuous Class-F mode is a promising solution for high-efficiency and wideband requirements. This mode provides multiple solutions by multiplication of drain voltage waveform of Class-F by the empirical factor $1 - \gamma \sin \theta$ as follows:

$$v_{DS}(\theta) = \left(1 - \frac{2}{\sqrt{3}} \cos \theta + \frac{1}{3\sqrt{3}} \cos 3\theta\right) \cdot (1 - \gamma \sin \theta) \quad (1)$$

For $\gamma = 0$, the standard Class-F voltage waveform is obtained with theoretical drain efficiency (DE) of 90.7%. Each value of γ represents particular loads at I-gen plane of device represented as [25]

$$Z_{1int} = \left(\frac{2}{\sqrt{3}} - j \cdot \gamma\right) \cdot R_{opt} \quad (2a)$$

$$Z_{2int} = j \frac{7\sqrt{3}\pi}{24} \gamma \cdot R_{opt} \quad (2b)$$

where Z_{1int} and Z_{2int} are the fundamental and second harmonic impedances, respectively. And the open circuit is presented to the third harmonic. R_{opt} is the optimal fundamental impedance of standard Class-B [26]. Each pair of Z_{1int} and Z_{2int} delivers the same output power and efficiency as standard Class-F.

3. Design space analysis at package plane

In practice, the impedance at package plane is preferred for actual PA circuit. By employing the typical package equivalent circuit, the theoretical design space can be transformed to the package plane as shown in Fig. 1. Z_{1pkg} and Z_{2pkg} are the fundamental and second harmonic impedances at the package plane, respectively. It can be seen

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Fig. 1. The optimal impedances at package plane with different frequencies.

(a)

(b)

Fig. 2. (a) Different k for the same starting value of $\gamma = -0.9$ and (b) their corresponding Z_{2pkg} .

that the rotation of fundamental and second harmonic impedances is anticlockwise as the frequency increases, especially the extent of second harmonic impedance is widely distributed. Therefore, it is impossible to be realized through the passive matching network. To overcome this problem, it is necessary to explore the design space by analyzing the parameter γ . There are three considerations: gradient of γ , range of γ and bandwidth of operating band.

(a)

(b)

Fig. 3. (a) Different ranges of γ and (b) their corresponding Z_{1pkg} and Z_{2pkg} .

Before analysis, k , the gradient of γ , is defined as the difference between successive values of γ for every successive change in frequency. Three different cases with different k have been shown in Fig. 2(a) and their corresponding Z_{2pkg} on the Smith chart in Fig. 2(b). In all cases, Δf is set to be 100 MHz to analysis the effect of k . And γ is set to -0.9 at 2 GHz for all cases. It can be seen that k can be positive or negative. A negative k makes the Z_{2pkg} follow an anticlockwise rotation as shown in Fig. 2(b). However, for $k = 0.05$, the extent of anticlockwise rotation reduces greatly and a clockwise rotation begins. This value is defined as threshold value. Considering the boundary of γ , there will be a boundary value of k , which is shown in Fig. 2(a). Any further increase in k will make the bandwidth decrease. For $k = 0.38$, only 500 MHz of band can be obtained. As discussed above, the constant value of k does not provide an good solution for the implementation of the matching network. Thus, a variable k is being investigated and the resultant values of Z_{2pkg} are shown in Fig. 2(b). Obviously, a variable k can provide a more feasible solution. Therefore, the impedance trajectory can be customized by changing the value of k at every frequency point to meet specific demand. It should be noted that the values of k are different for different range of γ .

In order to analysis range of the values of γ , three different cases are shown in Fig. 3(a); case A is $-1 \leq \gamma \leq -0.5$, case B is $-0.4 \leq \gamma \leq 0$, and case C is $0.1 \leq \gamma \leq 1$.

And the corresponding values of Z_{2pkg} are shown in Fig. 3(b). It can be seen that all cases can lead to clockwise rotation. For case A, however, the extent of clockwise rotation is very small, which is impossible to realize in wideband application. Therefore, the suitable range of γ is -1 to 0 . Although case B and case C have similar extent of rotation of the second harmonic impedances, case C is more suitable for the implementation of a passive network when considering the fundamental impedance matching.

4. PA design and measurement

(a)

(b)

Fig. 4. (a) The theoretical impedances at package plane and the output matching network impedance trajectories (b) The output matching network with the dimensions.

The 10W Cree CGH40010F device is used in this design to verify the proposed theory. The drain voltage is set at 28 V with a quiescent current of 106 mA. And a parallel circuit consisting of 47 Ω and 3.6 pF is employed to ensure the stability.

Based on the previous analysis, $-1 \leq \gamma \leq -0.17$ is selected and k is set as a variable. The value of k of each frequency and the resultant Z_{1pkg} and Z_{2pkg} are shown in Fig. 4(a). It can be seen that the fundamental loads are slightly to follow a clockwise rotation besides the clockwise rotation of the second harmonic loads. Therefore, these loads can be realized by passive matching network. The output matching network is composed of bandpass matching network [27] and step-impedance filtering transformer [28, 29]. And the tuning line is added to adjust the second harmonic impedances. It can be seen that the fundamental and the second harmonic impedances basically satisfy the theoretical impedance requirement, although some mismatches exist. Considering the nonlinear

Fig. 5. Photograph of fabricated circuit.

Fig. 6. Measured and simulated DE, output power, and gain.

characteristic of the drain-source capacitor, these mismatches are acceptable [30].

The circuit is realized on Roger's 4350B substrate with 3.66 as dielectric constant and 30 mil of height. Fig. 5 illustrates the photograph of the fabricated circuit. A 3.5 μ H 4310LC ferrite is used to supply very nice bias performance. Fig. 6 shows the measured and simulated large-signal test results over the whole bandwidth using an input power of 30 dBm. The simulated DE varies between 61.5% and 79.1% whereas the measured DE varies between 54.7% and 74.8% over the operating band from 1.7 to 3.0 GHz. Output power varies between 39.3–40.8 dBm and 39.7–41.1 dBm in simulation and measurement, respectively. The gain variation is between 9.7–11 dB in both simulation and measurement. The comparison with the recently reported broadband PA results is presented in Table I.

Table I. Comparison of some published PAs and our work

Ref	Bandwidth (GHz)	Power (dBm)	DE (%)	Gain (dB)
2016 [12]	2.85–4.25	40.7–42.0	58–78	10.8–12
2016 [13]	2.4–3.9	39.6–41.4	62.2–74.7	10.7–12.5
2017 [17]	2.5–4.1	39.6–42.6	47–75	8–14
2017 [18]	2.0–3.0	39.5–41.6	58–72	11.5–12.5
This work	1.7–3.0	39.7–41.1	54.7–74.8	9.7–11

5. Conclusion

This paper analyzes the design space of continuous Class-F mode at the package plane by using the package model. By parameterizing the empirical parameter γ by frequency, the impedance trajectories of fundamental and second harmonic can be modified to be more realizable for matching circuit. Based on this analysis, a highly efficient broadband PA has been fabricated displaying good performance.

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