Design of broadband high-efficient PA based on hybrid continuous modes

Chun Ni, Mingsheng Chen, Zhongxiang Zhang, Liang Zhang, Xianliang Wu

1School of Electronic and Information Engineering, Hefei Normal University, Hefei 230601, People’s Republic of China 2Anhui Engineering Research Center for Microwave and Communication, Hefei 230601, People’s Republic of China
E-mail: aiheping.student@sina.com

Published in The Journal of Engineering; Received on 1st November 2016; Accepted on 14th November 2016

Abstract: An ultra-wide band high-efficient power amplifier (PA) which employs both series of continuous modes and series of inverse continuous modes is presented for the first time. Consequently, the solutions space of fundamental impedance is expanded greatly. The operation frequency range of this mode can achieve more than two-octave bandwidth. Multistage transmission-line low-pass filter matching network has been utilised for matching fundamental impedance and suppressing of high-order harmonic. To verify this method, a high-efficient PA, which operates across 0.3–2.7 GHz (160% bandwidth) is designed. Simulation and experimental results show that the drain efficiency of this PA achieves 61.4–81.9%, and 8.3–16.6 W output power in the target band.

1 Introduction

The research of broadband high-efficient power amplifiers (PAs) has made great progress in recent years. Class-J PAs are proposed by Cripps in 2006 [1]. The fundamental impedance of class-J PAs is no longer a pure resistance, but a complex impedance with reactance component. On the basis of the class-J PAs, the concept of continuous PA is proposed by Cripps in 2009 [2]. The fundamental impedance of continuous PA is no longer a single impedance point. As a result, the solutions space of fundamental impedance is expanded greatly. Since then, the concept of continuous PA has been improved, and continuous class-F, continuous class-B/J, and the other continuous modes (SCMs) are proposed by many researchers.

With the help of non-linear model of device output capacitance and simplified real frequency technique, a continuous class-F PA with above 70% drain efficiency from 1.45 to 2.45 GHz (51% bandwidth) is designed by Tuffy in [3]. A hybrid PA mode is proposed in [4]. Continuous class-F and continuous inverse class-F are operated in two different bands, so that the bandwidth is expanded to more than an octave, and the drain efficiency of 60–84% is realised in the frequency range of 1.3–3.1 GHz. SCMs are composed of continuous class-F, continuous class-B/J, and the other continuous modes between them, leading in a greater space of fundamental impedance, more than continuous class-F [5]. With this method, a PA with 70.3–81.9% drain efficiency from 1.6 to 2.8 GHz is designed.

2 PA design methodology

The normalised drain currents of SCMs PAs are defined by (1), the same as Class-B PA. The normalised drain voltages of SCMs PAs are shown in (2)

\[
i_{\text{SCMs}}(\theta) = \frac{1}{\pi} + \frac{1}{3} \cos \theta + \frac{2}{3\pi} \cos 2\theta + \cdots
\]

\[
v_{\text{SCMs}}(\theta) = (1 - \alpha \cos \theta + \beta \cos 3\theta) \cdot (1 - \gamma \sin \theta)
\]

In (2), the value of variables \(\alpha\) and \(\beta\) determines the continuous mode of PA, while \(\alpha\) and \(\beta\) must satisfy a special relationship as indicated in (3). When \(\alpha = 1, \beta = 0\), the continuous mode is defined as the continuous Class-B/J operation [5]. When \(\alpha = 2/\sqrt{3}, \beta = 1/3\sqrt{3}\), the continuous mode are defined as the continuous Class-F [3]

\[
\alpha - \beta = 1 \quad \text{for} \ 1 \leq \alpha \leq 9/8
\]

\[
\alpha = \frac{2 + 2\beta}{\alpha} \sqrt{\frac{1}{4} + \frac{\alpha^2}{12\beta}} = 1 \quad \text{for} \ \alpha > 9/8
\]

The normalised drain currents of series of inverse continuous modes (SICMs) are defined by (4), where \(i_{\text{DC}} = 0.37, i_1 = 0.43\), and \(i_2 = 0.06\). The normalised drain voltages of SICMs are shown in (5)

\[
i_{\text{SICMs}}(\theta) = \left[i_{\text{DC}} - i_2 \cos \theta + i_1 \cos (3\theta) \cdot (1 - \delta \sin \theta)\right] - 1 \leq \delta \leq 1
\]

\[
v_{\text{SICMs}}(\theta) = 1 + \chi \cos \theta + \delta \cos 2\theta
\]

In (5), the values of variable \(\chi\) and \(\delta\) determine the continuous mode of PA, whereas \(\chi\) and \(\delta\) must satisfy a special relationship as indicated in (6). When \(\chi = \sqrt{2}, \delta = 1/2\), the PA is working under continuous inverse Class-F operation [6]

\[
\chi - \delta = 1, \quad \text{for} \ \chi \leq 4/3
\]

\[
\chi^2/8\delta + \delta = 1, \quad \text{for} \ \chi > 4/3
\]

The normalised voltages and currents of SICMs based on (1) and (2) are shown in Fig. 1a. Continuous Class-F voltage waveform is in blue curve; continuous Class-B/J voltage waveform in red; and currents waveform in black. The normalised currents and voltages of the SICMs based on (4) and (5) are shown in Fig. 1b. Continuous inverse Class-F voltage waveform is shown in green curve. When \(\chi = 6/5, \delta = 1/5\), the waveform is described by red curve, voltages waveform in black.

3 PA design and fabrication

To verify the above design method, an ultra-wide band PA working over 0.3–2.7 GHz is designed using CIIH40010F transistor. The gate and drain bias voltages are −2.5 and 28 V, respectively. The design procedure is based on substrate Rogers 4003C (\(e_r = 3.55, H = 32\) mil).

The fundamental and harmonic loads of SCMs are calculated by dividing voltage by current as shown in (1) and (2). The fundamental and harmonic loads of SICMs are calculated by dividing current by voltage as shown in (4) and (5). Here, \(R_{\text{opt}} = 36\), as shown in [5].
and $G_{opt} = 1/R_{opt}$. The space of fundamental impedance contains two parts, so the space has been expanded greatly. The calculated fundamental and harmonic loads of SCMs and SICMs are drawn in the Smith chart in Fig. 2. For a simple explanation, Fig. 2 just illustrates the fundamental impedance spaces when $\alpha = 1$, $\alpha = 2/\sqrt{3}$, $\chi = \sqrt{2}$, and $\chi = 6/5$ continuums.

The complete schematic of the PA including input and output matching network is shown in Fig. 3. By using the approximated equivalent network of device output parasitic for CGH40010F, the impedance trajectories of the output matching network at I-gen plane in Smith chart are shown in Fig. 2. The fundamental impedances from 0.3 to 2.7 GHz are in the optimum region. The photograph of the fabricated broadband PA is presented in Fig. 4. The simulated drain efficiency and output power from 0.3 to 2.7 GHz (160% bandwidth) are shown in Fig. 5. In the whole frequency range, the drain efficiency is >63.4% (maximum peak is 83.3% at 1.7 GHz). About 39.5–42.9 dBm of simulated output power is obtained.

The measured results are also illustrated in Fig. 5. The measured drain efficiencies across the whole working band are 61.4–81.9%. The measured output power is between 39.2 and 42.2 dBm. An average drain efficiency of 70% and an average output power of 41.3 dBm are achieved in 0.3–2.7 GHz.

4 Conclusions

A high-efficiency broadband PA based on SCMs and SICMs is presented. The space of fundamental impedance is expanded greatly by this new theory of design. A broadband PA that operates across 0.3–2.7 GHz (160% bandwidth) is designed. The measured
results show that the PA has achieved wide bandwidth of 0.3–2.7 GHz, with 61.4–81.9% drain efficiency, and 39.2–42.2 dBm output power within the bandwidth.

5 Acknowledgments

This work was supported by the National Natural Science Foundation of China (grant 51477039), the Key Projects of Natural Science of Anhui Provincial Education Department (grant KJ2015A292), and the Science and Technology Project of Anhui Province (grant 1501021041).

6 References

[1] Cripps S.C.: ‘RF power amplifiers for wireless communications’ (Artech House, Norwood, MA, 2006, 2nd edn.), pp. 67–89

[2] Cripps S.C., Tasker P.J., Clarke A.L., et al.: ‘On the continuity of high efficiency modes in linear RF power amplifiers’, IEEE Microw. Wirel. Compon. Lett., 2009, 19, (10), pp. 665–667

[3] Tuffy N., Guan L., Zhu A., et al.: ‘A simplified broadband design methodology for linearized high-efficiency continuous class-F power amplifiers’, IEEE Trans. Microw. Theory Tech., 2012, 60, (6), pp. 1952–1963

[4] Chen K., Peroulis D.: ‘Design of broadband high efficient harmonic tuned power amplifier using in-band continuous class-F\(^{-1}\)/F mode transferring’, IEEE Trans. Microw. Theory Tech., 2012, 60, (12), pp. 4107–4116

[5] Chen J., He S., You F., et al.: ‘Design of broadband high-efficiency power amplifiers based on a series of continuous modes’, IEEE Microw. Wirel. Compon. Lett., 2014, 24, (9), pp. 631–633

[6] Shi W.M., He S.B., Li Q.R.: ‘A series of inverse continuous modes for designing broadband power amplifiers’, IEEE Microw. Wirel. Compon. Lett., 2016, 26, (7), pp. 525–527