A Novel De-Embedding Technique of Packaged GaN Transistors

Abstract: This paper presents a novel de-embedding technique of packaged high-power transistors. With the proposed technique, the packaged model of the power amplifier (PA) tube can be divided into the frequency independent de-embedded intrinsic device (DID) and the frequency dependent internal parasitic network (IPN), which is of great help in reducing the design complexity of a broadband PA. Different from the conventional technique of parasitic extraction, the proposed technique only requires external measurements. The frequency independent characteristic of DID is verified and the IPN is modeled and calibrated for a 50 W gallium-nitride (GaN) transistor. At last, a broadband Doherty PA is fabricated with the de-embedding technique. According to the measured results, the PA exhibits satisfactory power and efficiency performance.

Keywords: de-embedding; power amplifier; intrinsic device; parasitic network

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1 Introduction

With the rapid development of wireless communications, especially the emerging 5G, the power amplifier (PA) is expected to handle broad bandwidth, high power, and high efficiency simultaneously. With advantages like large power capacity, high efficiency, and high breakdown voltage, gallium-nitride (GaN) power devices make themselves ideal candidates for such applications[1].

However, the traditional PA design is based on the packaged model of the power amplifier tube, as shown in Fig. 1. The output impedances of the packaged model vary significantly with frequency due to the parasitic characteristic of the packaged model, which complicates the matching network's design and limits the efficiency and bandwidth. While lots of the improved technologies were proposed to keep the parasitic low[2 – 6], it cannot be eliminated, and many parasitic compensation methods have been introduced[7 – 9].

For packaged power devices, the use of the parasitic de-embedding network to allow waveforms at the intrinsic plane is required. It is crucial when designing a complex power amplifier and investigating its performance. Several approaches were proposed to extract the extrinsic (package) parasitics, as
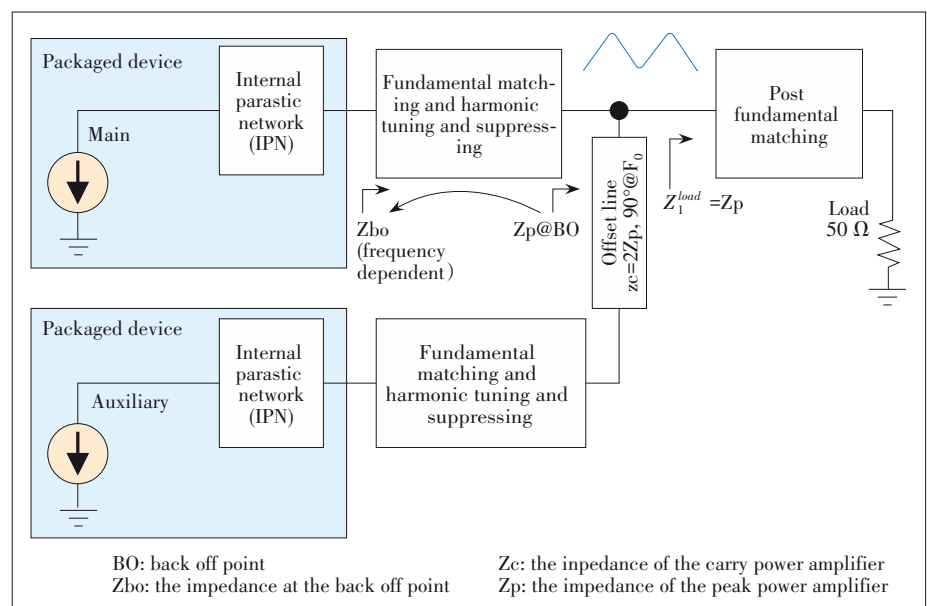
▲Figure 1. Conventional Doherty power amplifier (DPA) design

well as the intrinsic parasitics[10−14]. A de-embedding network of CGH40010F at 0.9 GHz was presented in Ref. [12]. It was derived through a combination of datasheet parameters and the manufacture's passive packaged models. It has been proved accurate enough at 2.1 GHz, but would result in an unacceptable error at a higher frequency. In Ref. [13], a de-embedding network of CGH40025F was proposed for applications up to 2 GHz. The previous work did not consider the effect of either the feedback capacitance or the inductance due to the gate and drain metallization. At higher frequencies, up to 3 GHz, these effects will impact the de-embedding accuracy. In Ref. [14], the parasitic model was only suitable for narrow bandwidth applications.

This work presents a novel de-embedding technique of packaged GaN transistors, which allows for accurate extraction of the device parasitic. The validation is carried out on a 50 W GaN transistor, which proves the effectiveness of the technique.

2 Proposed De-Embedding Technique

The packaged model of the packaged transistor can be divided into two parts through the de-embedding technique: the frequency independent nonlinear de-embedded intrinsic device (DID) and the frequency dependent linear internal parasitic network (IPN). The IPN can be absorbed into the matching circuit[14−15], as shown in Fig. 2. In this way, the design of the PA can be simplified and more accurate. In order to validate the technique, a 50 W GaN transistor is used as a validation in this work.

2.1 Parasitic Network Modeling

In order to extract the parasitic parameters of a dual-port network, the conventional method assumes that the IPN is completely unknown, and thus it needs to be measured in two cases, namely open and short circuits, as shown in Fig. 3a. Measurements should be taken inside the packaged model with special equipment, and C_{ds}, the capacitance between the drain and the source, cannot be calculated.

In this paper, we propose a novel single-port parasitic extraction method as shown in Fig. 3b. The parasitic network is modeled by passive components. The reflection coefficient of the external port Γopen is measured with the internal port of IPN open, and the values of components in the IPN model are obtained when Γmod is equal to Γopen. This method requires only external measurements to model a parasitic network without internal measurements. As shown in Fig. 4, the input and output parasitic networks of the 50 W GaN transistor are obtained with the proposed technique. The values of the components are listed in Table 1. Fig. 5 gives the small signal simulation results of the networks.

2.2 DID Model Calibration

In the proposed de-embedding technique, the parasitic parameter network is obtained through the large signal parametric model simulation. However, the accuracy of IPN is poorer compared with that of DID. In order to improve the accuracy, the model should be calibrated. We can measure the packaged transistor with a precise fixture, and thus an accurate parasitic parameter model is obtained by parasitic parameter modeling.

The 50 W GaN transistor is measured using a 6.9 Ω through reflection line (TRL) measurement fixture, as shown in Fig. 6. The calibrated accurate parasitic parameter model is shown in Fig. 7. The values of the components are listed in Table 2.
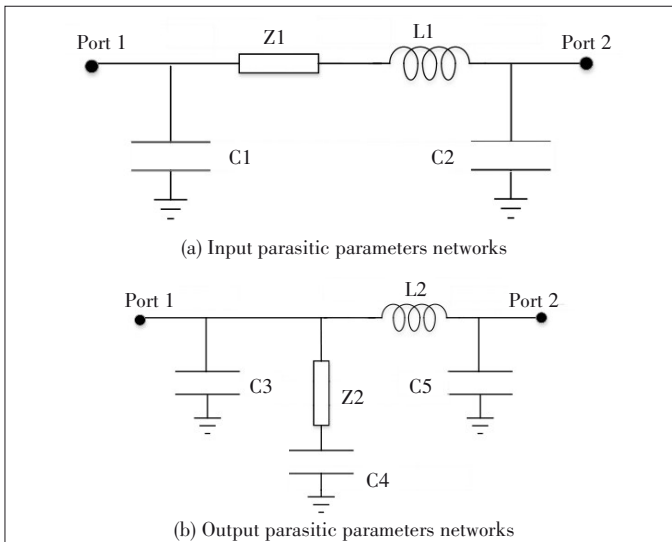
2.3 DID Model Verification

According to the parasitic network model, the DID model can be obtained. Considering the DID model is frequency in-
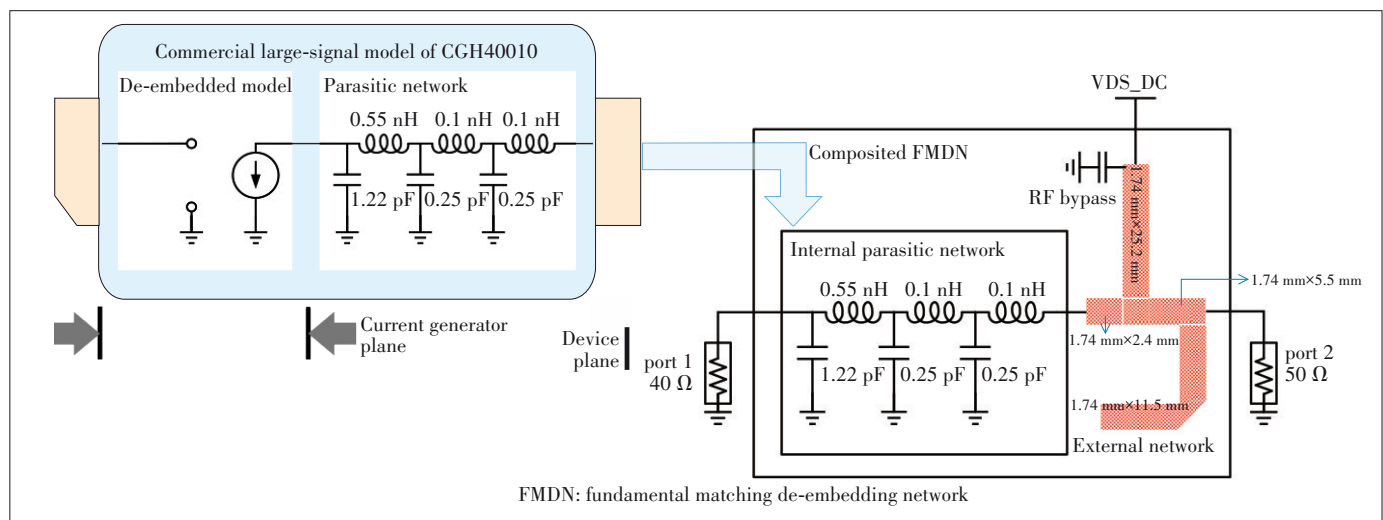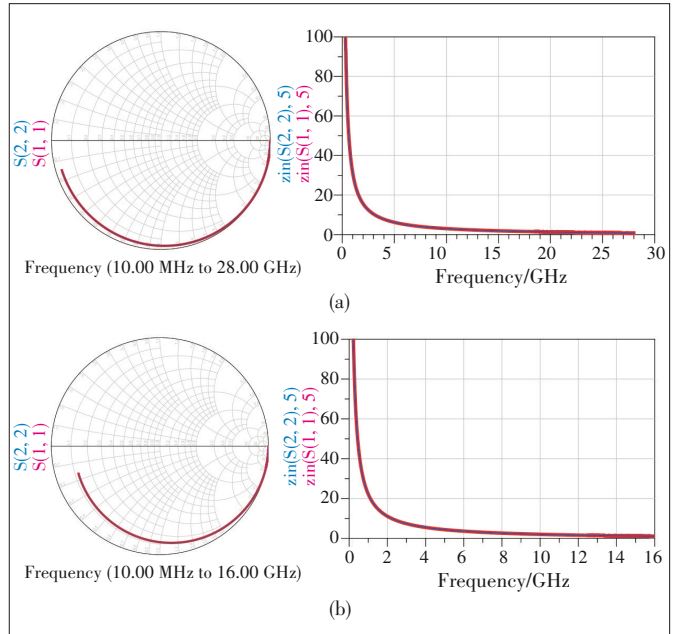

▲Figure 2. De-embedding technique of packaged model
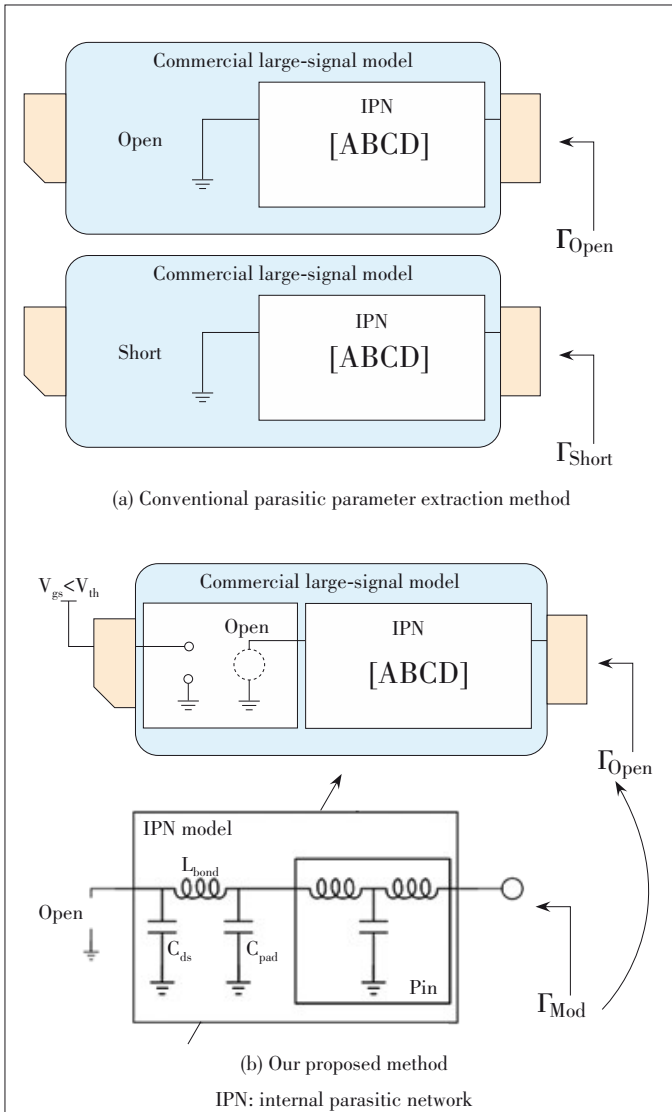
▲Figure 3. Methods to extract parasitic parameters

▲Figure 4. Input and output parasitic parameters networks

▼Table1. Values of the components in the parasitic model

Component	Value	Component	Value
Z1	0.36 Ω	C2	11.93 pF
Z2	6.05 Ω	C3	1.88 pF
L1	3.44 pH	C4	609.68 fF
L2	5.29 pH	C5	61.41 fF
C1	4.18 fF		

▲Figure 5. Small signal simulation results of (a) the input network and (b) the output network
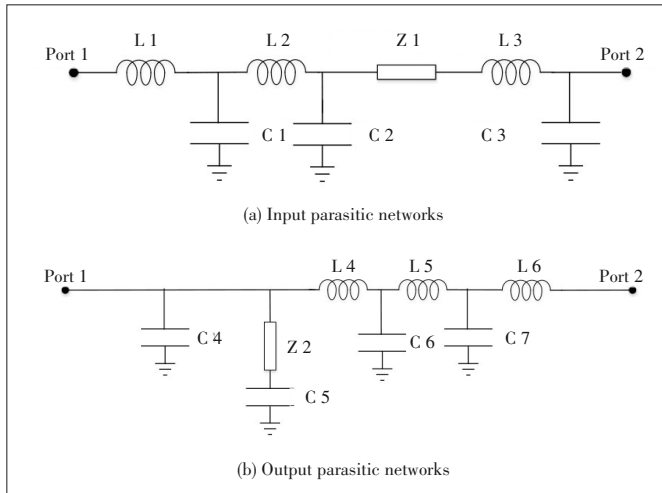

▲Figure 6. The 6. 9 Ω through reflection line (TRL) measurement fixture

dependent, the design of broadband DPA can be significantly simplified. In order to verify the frequency independent characteristics of DID, the DID model of the 50 W GaN power tubes is simulated over a wide frequency range of 500 – 5 000 MHz. The simulation results are shown in Fig. 8. It can be seen from Fig. 6 that the output power, efficiency, and gain performance are independent of frequency in the wide frequency range of 500 – 5 000 MHz. The DID model gives the ideal frequency in-dependent characteristics and the proposed de-embedding

technique is confirmed.

could be a great demonstration of the proposed technique.

3 DPA Design

In order to verify the effectiveness of the de-embedding technique, a broadband Doherty PA using the 50 W GaN transistor is designed and fabricated utilizing the de-embedded model. The demonstrating 200 W DPA is designed at the range of 1.7 – 2.7 GHz. The fabricated DPA is measured using continuous wave (CW) signals and the measured drain efficiency and power gain are shown in Fig. 9. The designed PA exhibits satisfactory power and efficiency performance, which

4 Conclusions

In this paper, a novel de-embedding technique of packaged GaN transistors is proposed and verified. The technique di-

▲Figure 7. Calibrated accurate parasitic parameter model

▼Table 2. Values of the components in the calibrated model

Component	Value	Component	Value
Z1	0.56 Ω	C1	1.90 pF
Z2	26.39 Ω	C2	196.27 fF
L1	128.22 pH	C3	9.97 pF
L2	492.62 pH	C4	3.73 pF
L3	15.04 pH	C5	17.53 fF
L4	460.77 pH	C6	1.47 pF
L5	52.70 pH	C7	571.46 fF
L6	108.9 pH		
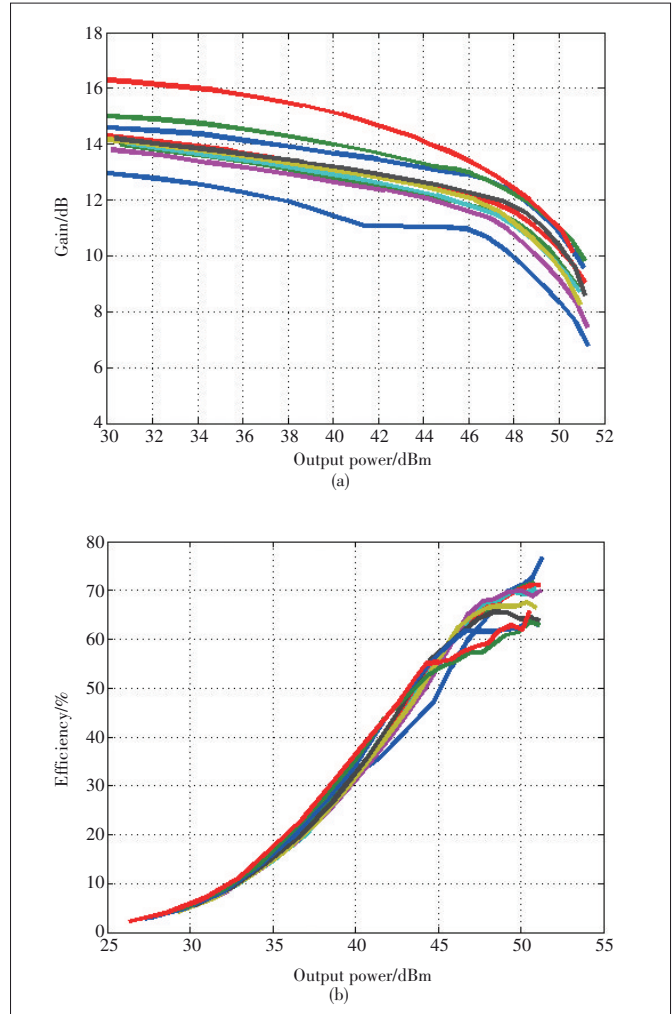
▲Figure 9. Measured (a) drain efficiency and (b) gain of the fabricated DPA
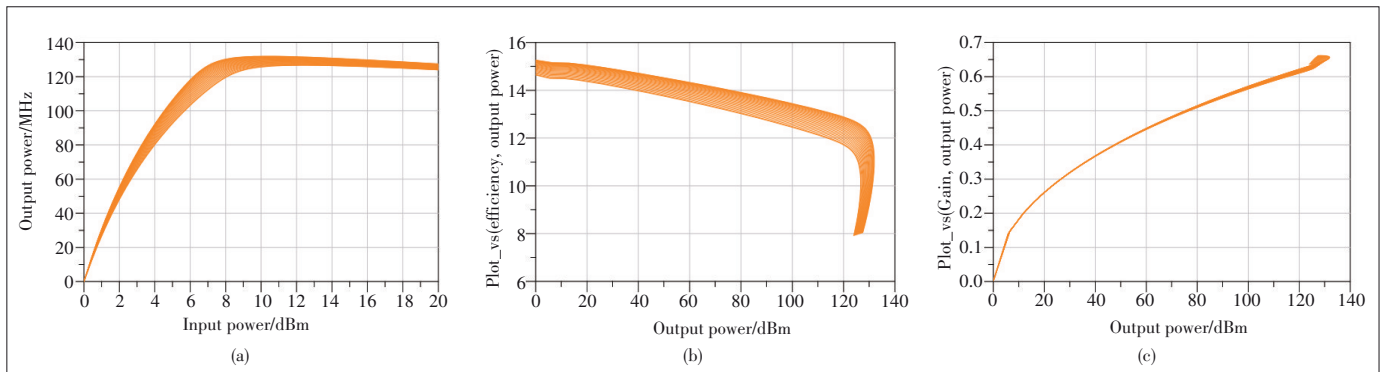
▲Figure 8. Simulation results: (a) output power; (b) efficiency; (c) gain

vides the packaged device into the frequency independent DID and frequency dependent IPN, which only requires external measurements. The IPN can be absorbed into the matching circuit, thus the PA design is only based on the DID. Considering the frequency independent characteristic of DID, the method greatly simplifies the design of efficient wideband PA.

Regarding the rationale, this method could be expanded to other packaged microwave power devices.

References

[1] PENGELLY R S, WOOD S M, MILLIGAN J W, et al. A review of GaN on SiC high electron‑mobility power transistors and MMICs [J]. IEEE transactions on microwave theory and techniques, 2012, 60(6): 1764 – 1783. DOI: 10.1109/TMTT.2012.2187535

[2] HO S W, YOON S W, ZHOU Q, et al. High RF performance TSV silicon carrier for high frequency application [C]//Electronic Components and Technology Conference. Lake Buena Vista, USA, 2008: 1946 – 1952. DOI: 10.1109/ECTC.2008.4550249

[3] WU J H, ALAMO J ADEL. Fabrication and characterization of through‑substrate interconnects [J]. IEEE transactions on electron devices, 2010, 57(6): 1261 – 1268. DOI: 10.1109/TED.2010.2045671

[4] DONG S, TASKER P J, WANG G, et al. A practicable de‑embedding network at higher frequency of a packaged GaN device [C]//IEEE MTT‑S International Wireless Symposium (IWS). Shanghai, China: IEEE, 2016: 1 – 4. DOI: 10.1109/IEEE-IWS.2016.75854735

[5] KAKKAD P, AGGRAWAL E, RAWAT K. De‑embedded model based class‑E power amplifier using waveform engineering [C]//International Conference on Computing, Communication and Networking Technologies (ICCCNT), Delhi, India, 2017: 1 – 4. DOI: 10.1109/ICCCNT.2017.8204012

[6] DONG S W, LEES J, TASKER P J. A de‑embedding network at higher frequency and its error analysis [C]//2016 IEEE International Conference on Electronic Information and Communication Technology (ICEICT). Harbin, China: IEEE, 2016: 512 – 514. DOI: 10.1109/ICEICT.2016.7879754

[7] LEE Y S, LEE M W, JEONG Y H. High-efficiency class-F GaN HEMT amplifier with simple parasitic-compensation circuit [J]. IEEE microwave and wireless components letters, 2008, 18(1): 55 – 57. DOI: 10.1109/LMWC.2007.912023

[8] LIU C, CHENG Q F. A novel compensation circuit of high-efficiency concurrent dual-band class-E power amplifiers [J]. IEEE Microwave and Wireless Components Letters, 2018, 28(8): 720 – 722. DOI: 10.1109/LMWC.2018.2842686

[9] SAYED A S, AHMED H N. Wideband high efficiency power amplifier design using precise high frequency GaN-HEMT parasitics modeling/compensation[C]//2019 IEEE Topical Conference on RF/Microwave Power Amplifiers for Radio and Wireless Applications (PAWR). Orlando, FL, USA: IEEE, 2019: 1-4. DOI: 10.1109/PAWR.2019.8708722

[10] DAMBRINE G, CAPPY A, HELIODORE F, et al. A new method for determining the FET small‑signal equivalent circuit [J]. IEEE transactions on microwave theory and techniques, 1988, 36(7): 1151 – 1159. DOI: 10.1109/22.3650

[11] YUAN Y, ZHONG Z, GUO Y X, et al. A novel hybrid parameter extraction method for GaAs/GaN HEMT modeling with electromagnetic analysis [C]//2015 Asia‑Pacific Microwave Conference (APMC). Nanjing, China: IEEE, 2015: 1 – 3. DOI: 10.1109/APMC.2015.7413224

[12] TASKER P J, BENEDIKT J. Waveform inspired models and the harmonic balance emulator [J]. IEEE microwave magazine, 2011, 12(2): 38 – 54. DOI: 10.1109/MMM.2010.940101

[13] CHEN K L, PEROULIS D. Design of highly efficient broadband class-E power amplifier using synthesized low-pass matching networks [J]. IEEE transactions on microwave theory and techniques, 2011, 59(12): 3162 – 3173. DOI: 10.1109/TMTT.2011.2169080

[14] KURODA K, ISHIKAWA R, HONJO K. Parasitic compensation design technique for a C-band GaN HEMT class-F amplifier [J]. IEEE transactions on microwave theory and techniques, 2010, 58(11): 2741 – 2750. DOI: 10.1109/TMTT.2010.2077951

[15] WU D Y T, BOUMAIZA S. A modified Doherty configuration for broadband amplification using symmetrical devices [J]. IEEE transactions on microwave theory and techniques, 2012, 60(10): 3201 – 3213. DOI: 10.1109/TMTT.2012.2209446

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