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An X-Band 40 W Power Amplifier GaN MMIC Design by Using Equivalent Output Impedance Model

Ruitao Chen [1], Ruchun Li [1], Shouli Zhou [1,*], Shi Chen [2], Jianhua Huang [2] and Zhiyu Wang [2]

1 College of Information Engineering, Zhejiang University of Technology, Hangzhou 310023, China; rtchen@zjut.edu.cn (R.C.); lrc@zjut.edu.cn (R.L.)
2 School of Aeronautics and Astronautics, Zhejiang University, Hangzhou 310027, China; schen_iaee@zju.edu.cn (S.C.); oscarhua@zju.edu.cn (J.H.); zywang@zju.edu.cn (Z.W.)
* Correspondence: zhoushl@zjut.edu.cn; Tel.: +86-0571-8529-0605

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Abstract: This paper presents an X-band 40 W power amplifier with high efficiency based on 0.25 μm GaN HEMT (High Electron Mobility Transistor) on SiC process. An equivalent RC (Resistance Capacitance) model is presented to provide accurate large-signal output impedances of GaN HEMTs with arbitrary dimensions. By introducing the band-pass filter topology, broadband impedance matching networks are achieved based on the RC model, and the power amplifier MMIC (Monolithic Microwave Integrated Circuit) with enhanced bandwidth is realized. The measurement results show that this power amplifier at 28 V operation voltage achieved over 40 W output power, 44.7% power-added efficiency and 22 dB power gain from 8 GHz to 12 GHz. The total chip size is 3.20 mm × 3.45 mm.

Keywords: X-band; GaN; power amplifier; MMIC

1. Introduction

Broadband power amplifiers with high efficiency are key components employed widely in modern electric systems such as phased array radar and high-power electronic warfare systems [1–3]. The GaN HEMT, with high electron mobility and high breakdown voltage, has a higher output impedance, which brings many benefits for broadband matching.

The accuracy of the GaN HEMT model is especially important for broadband power amplifier designs. Within the model, the output impedance of the GaN HEMT is one of the key parameters that decide the quality of the broadband matching and bandwidth enhancement. However, to obtain accurate large-signal models for GaN, HEMTs are always big problems especially in board level designs with discrete transistors [4–6]. The MMIC designers usually figure out a transistor's output impedance by performing a large-signal simulation. The complex impedance can hardly characterize the transistor physically, and makes it quite difficult to analyze the broadband matching network topology.

To deal with the above problems, in this paper, an equivalent RC model of active devices' large-signal output impedance is presented that demonstrates a high accuracy of the output impedance of the GaN HEMT. The RC model has a certain physical meaning for representing the active devices that have current and voltage swing limitations, and enables a practical broadband matching network design [7]. An 8–12 GHz broadband power amplifier manufactured using 0.25 μm GaN HEMT on SiC process is designed based on the RC model. The design of broadband impedance matching networks of the power amplifier is described in detail. To verify the accuracy of the RC model, we conduct load-pull and S-parameters measurements. Based on the RC model, accurate output impedances of GaN HEMTs with arbitrary dimensions can be achieved by scaling up gate periphery. The measurement results show that the proposed power amplifier achieved excellent performance with more than 40 W output power and 44.7% power-added efficiency over a bandwidth from 8 GHz to 12 GHz.

2. Output Impedance Model and Validation

The large-signal output impedance of the active devices can be equivalent to a parallel RC model, as shown in Figure 1. According to the load line theory, the power point R_p is estimated as Equation (1) [8]. In this GaN process, the maximum current I_{max} and the knee voltage V_{knee} are 0.8 *A/mm* and 5 *V*, respectively. Table 1 shows that the parameters of 0.25 µm GaN HEMT process. The theoretical power point R_p value is about 58 $\Omega \cdot mm$ at 28 *V* operating voltage.

$$R_p = \frac{2(V_{dd} - V_{knee})}{I_{\max}} \tag{1}$$

$$C_p = C_{ds} + C_{gd}(1 - 1/K_u) \approx C_{ds} + C_{gd} \tag{2}$$

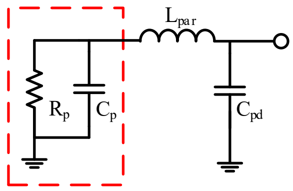

Figure 1. RC model of active devices' large-signal output impedance.

Table 1. The parameters of 0.25 µm GaN HEMT process.

Parameter	Value	Parameter	Value
V_{TH} (V)	−2.9	f_t (GHz)	24.5
V_{BDG} (V)	121	f_{max} (GHz)	75
I_{dmax} (mA/mm)	800	$P_{density}$ (W/mm)	5
Gm_Peak (mS/mm)	390	C_{MIM} (pF/mm^2)	215

The C_p is mainly composed of the output equivalent capacitance C_{ds} and C_{gd}, as in Equation (2). Where K_u is the voltage gain. The capacitance C_{ds} and C_{gd} are 0.3 *pF/mm* and 0.1 *pF/mm*, respectively. The optimal C_p value of the efficiency and power are close, and the value is about 0.4 *pF/mm*. To verify the accuracy of the RC model, we conducted load-pull and S-parameters measurements. The RC values of the large-signal output impedance are extracted through the load-pull and S-parameters measurement data of the GaN HEMTs, as shown in Figure 2. The admittance Y of looking into the device is given by Equation (3).

$$Y = \frac{1}{Z^*} = G + j * B \tag{3}$$

where Z is the load pull impedance. The RC extraction formulas are shown Equations (4) and (5).

$$R_p = \frac{W}{G}(\Omega \cdot mm) \tag{4}$$

$$C_p = \frac{B}{\omega \cdot W}(pF/mm) \tag{5}$$

where W is the total gate periphery and ω is the angular frequency. The R_p tends to decrease with increasing frequency. Based on the above theory, the RC model is compared with the measured and the GaN HEMT PDK model data, as shown in Figure 3. For large-signal output impedance, the RC model has higher accuracy than the GaN HEMT PDK model provided by the factory. In addition, the RC model supports the accurate extraction of the large-signal output impedances of GaN HEMTs with arbitrary dimensions. Therefore, in the following design of the broadband impedance matching networks of a GaN HEMT power amplifier MMIC, the RC model is directly used to replace the PDK model as the large-signal output impedance of the GaN HEMT.

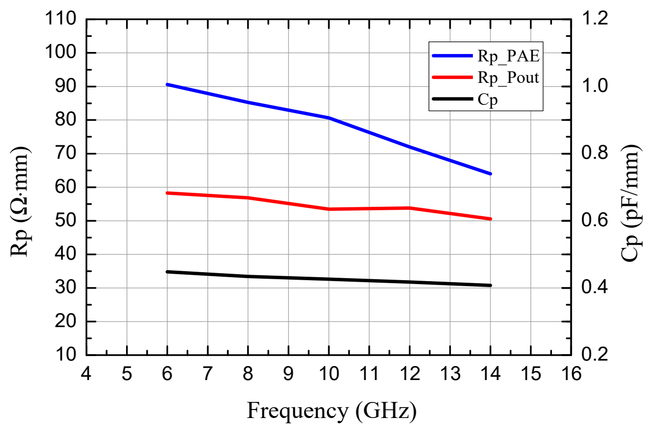

Figure 2. The R_p and C_p parameters versus frequency.

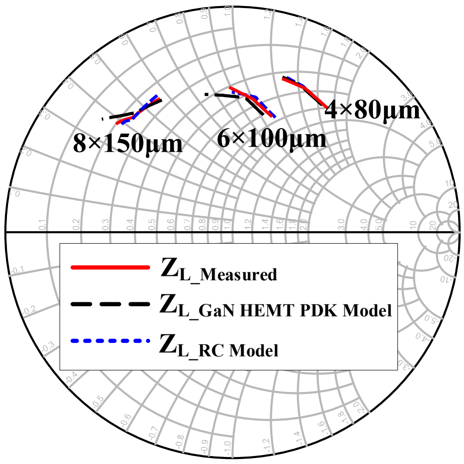

Figure 3. Comparison of 8–12 GHz optimal efficiency point impedance with measured, RC model, and GaN HEMT PDK model.

3. Circuit Design

The circuit topology of the proposed power amplifier is shown in Figure 4. The circuit design consists of two stages. The first stage and the second stage use the same HEMT of 8 × 150 µm total gate periphery, and the periphery ratio is 1:4. The RC values of the 8 × 150 µm GaN HEMT are about 70 Ω and 0.45 pF, respectively.

The L-R-C networks are used to guarantee the overall stability of the power amplifier and reduce the Q factor of the matching network. The gain response of the GaN HEMT decreases as the frequency increases, thus the L-R-C networks were designed to provide the compensation of gain flatness. The output matching network is designed to transfer to 50 ohm to equivalent parallel RC model, as shown in Figure 5. To achieve the maximum output power, the output matching network utilizes the band-pass filter topology to reduce the insertion loss. The inter-stage matching network is achieved by using band-pass filter topology to extend the bandwidth [9], as shown in Figure 6. In addition, the equivalent impedance is usually obtained by the Norton transformer network. In the second stage, the resistors are used between each GaN HEMT in order to prevent odd mode oscillation.

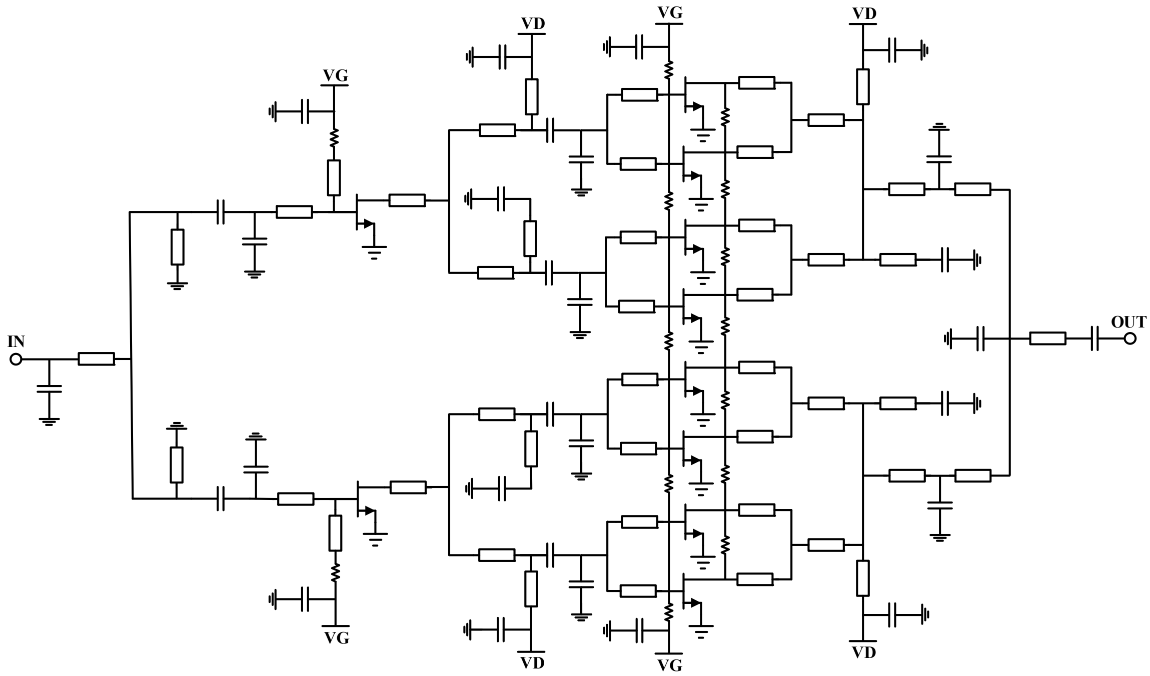

Figure 4. The circuit topology of the power amplifier.

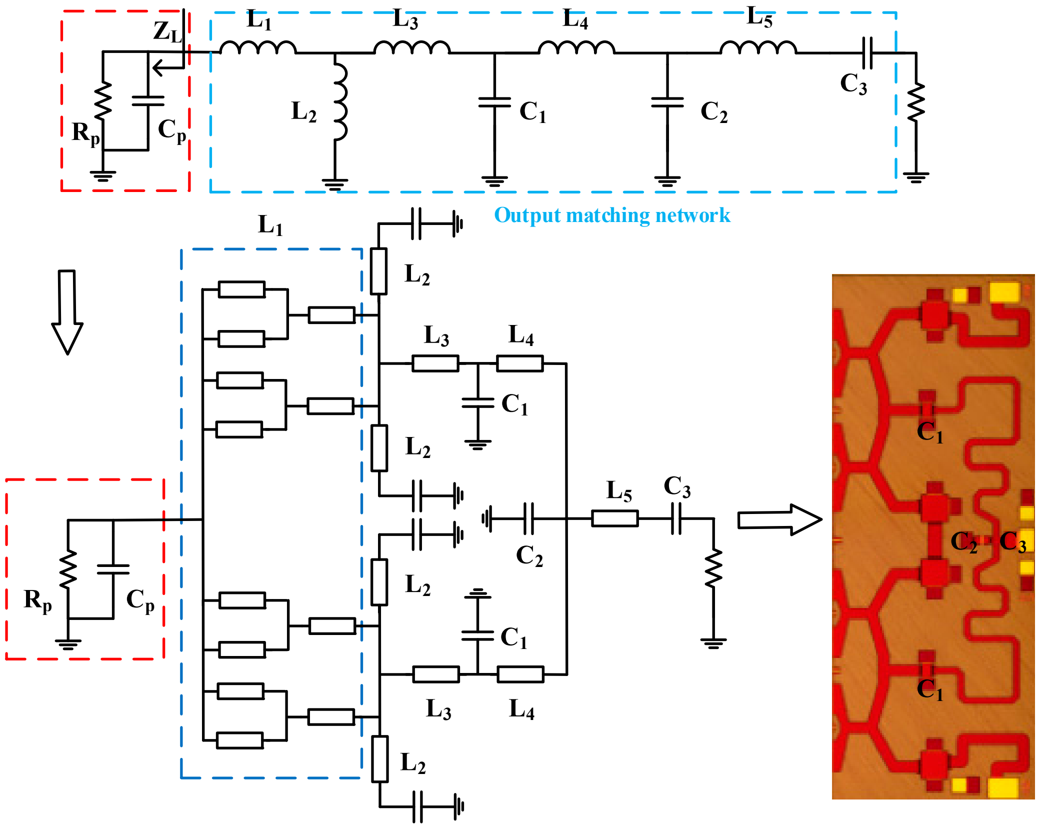

Figure 5. Output matching network.

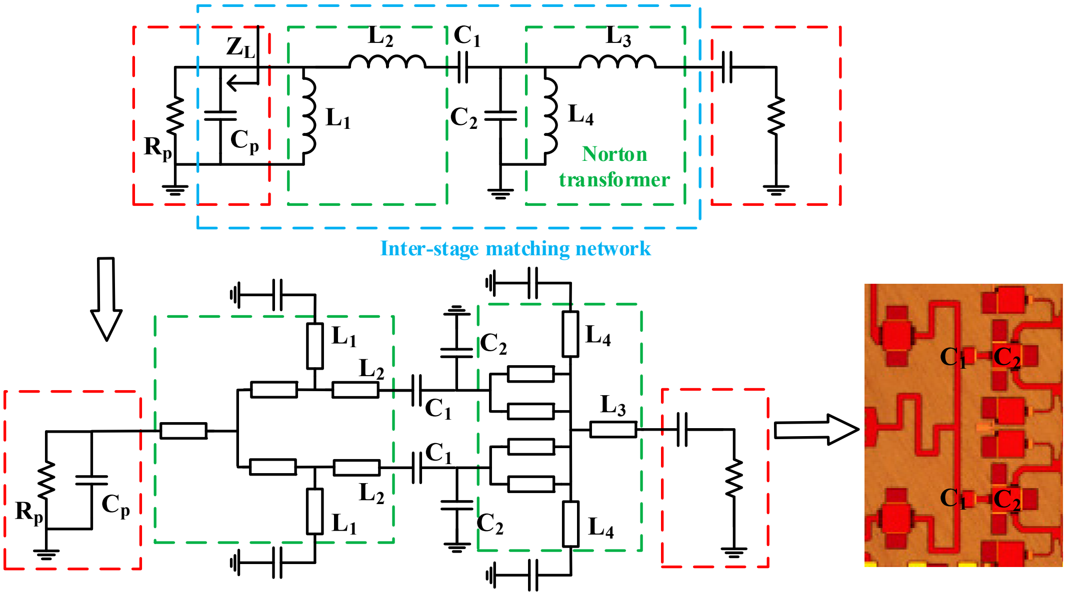

Figure 6. Inter-stage matching network.

4. Measurement Results

The proposed power amplifier chip photograph is shown in Figure 7, and the total chip size is 3.20 mm × 3.45 mm. The drain and gate voltage bias of the power amplifier are 28 V and −2 V, respectively. The power amplifier measurements are performed under pulsed conditions with 100 µs pulse width and 10% duty cycle.

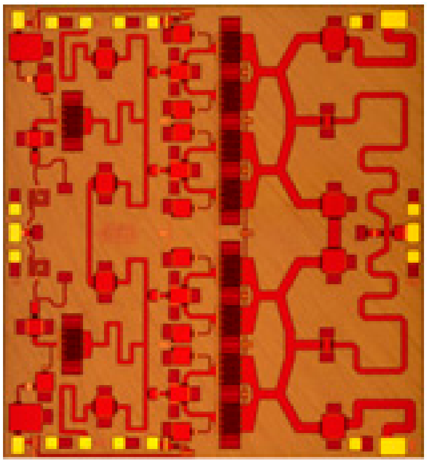

Figure 7. Photograph of X-band 40W power amplifier.

The average saturated output power is over 40 W from 8 GHz to 12 GHz with 24 dBm input power, as shown in Figure 8a. The associated average power-added efficiency is over 44.7% and the peak power-added efficiency is 51.4% at 8.1 GHz. The small signal gain varies in the range of 24.5 dB to 28 dB and the input reflection coefficient stays below −12.7 dB, as shown in Figure 8b. The measured output power, gain and PAE of the power amplifier versus the input power at 8.8 GHz are shown in Figure 8c. With 26 dBm input power, this power amplifier achieved 52 W output power and 50% power-added efficiency at 8.8 GHz. The measured output power, gain and PAE of the power amplifier versus the input power at 10.4 GHz are shown in Figure 8d. With 26 dBm input power, this power amplifier achieved 43 W output power and 44.5% power-added efficiency at 10.4 GHz. Table 2 summarizes the performance comparison of this power amplifier with the previous published power amplifiers at close frequency ranges. The characteristics of the proposed power amplifier includes power, power-added efficiency, power gain, and size.

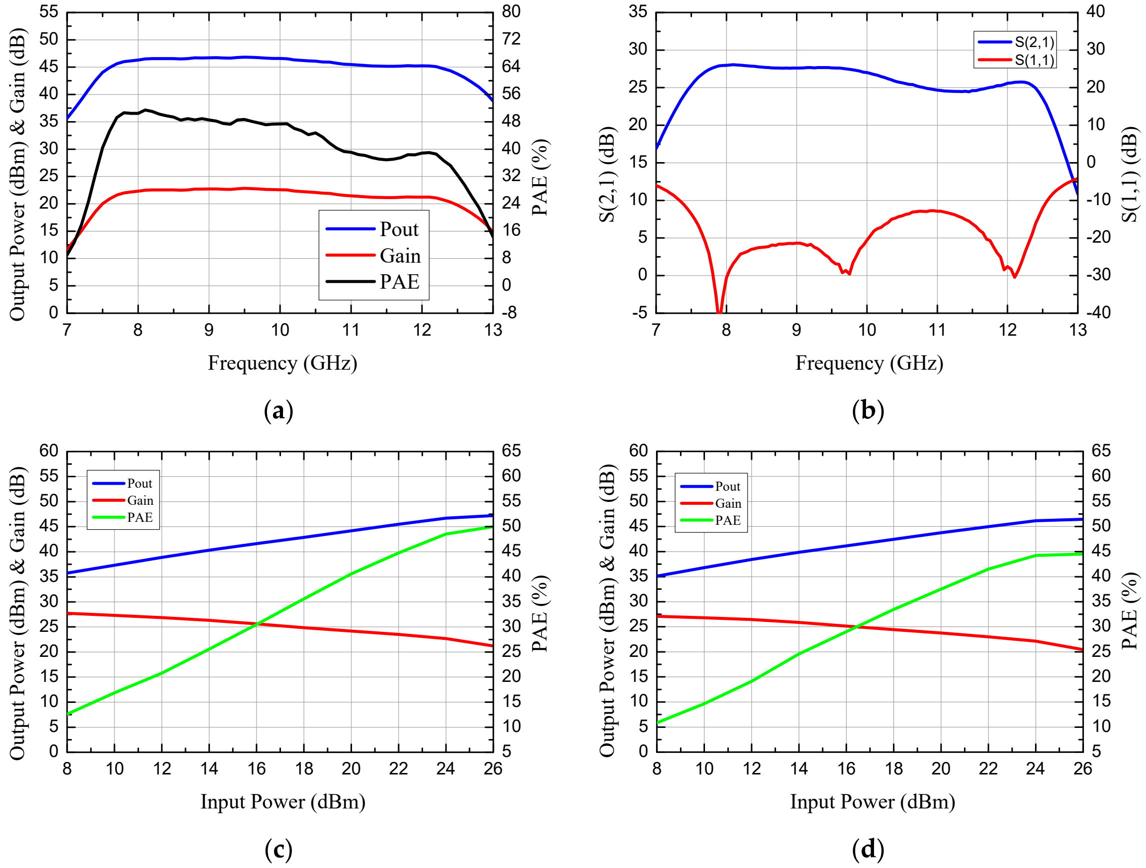

Figure 8. (**a**) Measured output power, gain, and PAE versus frequency at 24 dBm input power; (**b**) Measured S-parameter versus frequency; (**c**) Measured output power, gain, and PAE versus input power at 8.8 GHz frequency; (**d**) Measured output power, gain, and PAE versus input power at 10.4 GHz frequency.

Table 2. Performance comparison of relevant power amplifiers.

Reference	Process	Frequency (GHz)	Pout (W)	PAE (%)	G_p (dB)	Stage	Pulse/Duty (µs, %)	Size (mm^2)
[10]	0.25 µm GaAs	8.25–10.25	10.7	41.4	19	2	3, 3	4.41 × 2.5
[11]	0.25 µm GaN	8.8–10.4	14	38	18	2	50, 15	4.5 × 4.0
[12]	0.5 µm GaN	8–10.5	20	35	15	2	100, 25	5.0 × 3.2
[13]	0.5 µm GaN	8.5–9	30	40	14	2	10, 1	5.33 × 3.5
[14]	0.25 µm GaN	8.5–10.5	35	40	14	2	20, 10	4.5 × 4.0
[15]	0.25 µm GaN	8.8–10.8	40	44	17	2	100, 10	4.5 × 4.6
This work	0.25 µm GaN	8–12	40	44.7	22	2	100, 10	3.20 × 3.45

5. Conclusions

In this paper, the design of a broadband 40 W power amplifier MMIC over a bandwidth from 8 GHz to 12 GHz is reported. An equivalent RC model is presented which can accurately extract the output impedance of GaN HEMTs and can be used to achieve the broadband matching networks of the power amplifier. The band-pass filter topology is employed to achieve the maximum output power and extend the bandwidth. The measurement results show that this power amplifier has excellent performance with over 40 W output power and 44.7% power-added efficiency at operation frequency.

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Conflicts of Interest: The authors declare no conflict of interest.

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