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A 17–26.5 GHz 42.5 dBm broadband and highly efficient gallium nitride power amplifier design

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A gallium nitride (GaN) power amplifier monolithic microwave integrated circuit (MMIC) with a wide band and high efficiency in the microwave frequency band is proposed in this study. The power amplifier MMIC uses a 0.15 μm GaN high electron mobility transistor (HEMT) process. The operating frequency band of the amplifier can cover the whole K-band, i.e., 17–26.5 GHz. To obtain better output power and power added efficiency (PAE), the power amplifier MMIC is designed with the optimal driving ratio of the front and rear stages and the optimal size of the transistor according to the performance of the transistor, and a broadband low-loss circuit topology is adopted to realize the broadband high-efficiency design. The harmonic control structure is integrated into the drive-stage matching circuit to improve the high-frequency efficiency and keep the PAE high performance in the whole frequency band. In the continuous wave (CW) mode, results show that the power amplifier, using a three-stage topology, demonstrates over 42.5 dBm saturated output power in the frequency range of 17–26.5 GHz, an average PAE of 30%, and the maximum value of PAE is 32.1% at 19.8 GHz. The output power flatness is better than 1.0 dB. The chip has a compact structure and an area of 4.2 mm×3.0 mm, and can be widely used in transceiver components, wireless communications, electronic measuring instruments, etc.

1 Introduction

A wideband power amplifier is one of the key components in mobile communication systems and radar systems because it is a key component of radio frequency (RF) front-end systems, and its performance occupies a dominant position in the entire system function. GaN as the representative of the third generation of wide band gap semiconductors has the advantages of wide band gap, high electron mobility, and high breakdown field strength (Mishra et al., 2008; Millán et al., 2014). The power density of the device far exceeds that of Si and GaAs. Because of its high frequency, high power, high efficiency, high temperature resistance, high radiation resistance, and other excellent characteristics, GaN MMICs have broad application prospects in the microwave and millimeter wave bands.

Because of the high breakdown voltage and high power density of a GaN HEMT, broadband high-efficiency power amplifiers made using this process have gained increasing attention in wireless communication systems and phased array radar systems. So

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far, with the use of distributed structures (Campbell et al., 2009; Komiak et al., 2011) and various matching techniques, such as reactive filter synthesis and real-frequency technology (Chen and Peroulis, 2011; Xia et al., 2014; Dai et al., 2015), broadband GaN power amplifiers have been reported in a lot of papers. Distributed power amplifiers have significant advantages in terms of return loss and broadband performance. However, they are affected by inherent low power and large size, making them unsuitable for low-cost and high-power applications. Compared with the distributed power amplifier, the power amplifier with broadband low-loss reactance matching technology can obtain higher power and higher efficiency.

To broaden the working bandwidth of a GaN power amplifier in the K-band and improve the working efficiency in the whole frequency band, in this study we propose a broadband high-power and high-efficiency GaN power amplifier, which covers the whole K-band by using gain equalization technology and broadband low-loss topology design considering harmonic matching. In the frequency range of 17–26.5 GHz, the broadband power amplifier has over 42.5 dBm saturated output power, and the output power flatness is less than 1 dB. An average PAE of 30% and over 17.5 dB power gain are demonstrated in the entire frequency band.

2 Design of the power amplifier MMIC

The power amplifier MMIC adopts 0.15 μm GaN HEMT technology. The RF characteristics of transistors are characterized by the load-pull test results of 4×80 μm transistor cells at V_{DS}=20 V as shown in Table 1.

Table 1 The RF characteristics of 4×80 μm transistor cells

Freq. (GHz)	Peak P_{out} (dBm)		Peak PAE (%)		Gain (dB)	
	Max. P_{out}	Max. PAE	Max. P_{out}	Max. PAE	Max. P_{out}	Max. PAE
18	32.9	32.4	46.3	49.3	10.9	10.4
22	32.2	31.9	40.9	43.6	9.2	8.9
26	32.3	32.1	37.6	39.1	8.3	8.1

The results show an output power density of larger than 6.1 W/mm and a peak PAE of 49.3% with 10.4 dB power gain at 18 GHz, an output power density of larger than 5.2 W/mm and a peak PAE of 43.6% with 8.9 dB power gain at 22 GHz, and an output power density of larger than 5.3 W/mm and a peak PAE of 39.1% with 8.1 dB power gain at 26 GHz.

One of the design goals for a wideband amplifier is to maintain the gain flatness over a wide frequency range. In the design, the most common problem is that the S_{21} of the device changes with frequency. In the most typical case, S_{21} decreases by 6 dB with frequency per octave. Therefore, it is necessary to design an appropriate matching network to compensate for the change of S_{21} with frequency. Therefore, we adopt a multistage cascade mode, use a reactance matching circuit to design the inter-stage matching network, and provide a gain varying with frequency according to the positive slope to compensate for the gain roll-off effect of the transistor, so that the amplifier has a flat frequency response over the whole frequency band. Fig. 1 shows the design idea and structure of the three-stage GaN power amplifier.

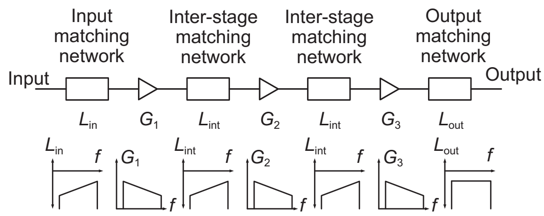

Fig. 1 The design idea and structure of a typical three-stage power amplifier

G_1, G_2, and G_3 represent the gains of the first, second, and third stages, respectively, L_{in}, L_{int}, and L_{out} represent the loss of input, inter-stage, and output matching networks, respectively, and f represents the frequency

The efficiency of a power amplifier depends mainly on the design of the output matching circuit. On one hand, it depends on the impedance matching of the output-stage transistor; on the other hand, it depends on the insertion loss of the output matching network. Because of the characteristics of device technology, the best-efficiency impedance and the best-power impedance of GaN HEMT are not the same, so for the impedance selection of the output matching network we often need to make a compromise between the best efficiency and the best power. To achieve the highest efficiency, it is necessary to match the best-efficiency point and sacrifice part of the power characteristics. To reduce the insertion loss, in the output matching topology of the power amplifier, second-order LC impedance transformation and busbar bias structure are used to achieve broadband low-loss impedance matching. The layout of the output matching network is shown in Fig. 2.

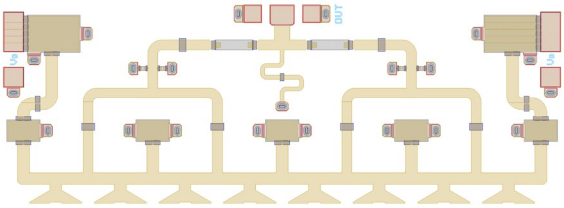

Fig. 2 Layout of the output matching network

The electromagnetic field simulation results of the output matching network in the Smith chart and output matching loss in the Cartesian coordinate system are shown in Fig. 3.

The design of the third-stage matching circuit also plays an important role in improving the efficiency of the whole power amplifier. First, the matching network should satisfy the optimal input matching impedance design of the final-stage transistor. Also, note that the second harmonic control structure is integrated into the third-stage matching circuit structure. Specifically, as a part of the third-stage matching network, the series LC resonant network is placed at the input of the output-stage transistor, as shown in Fig. 4. By optimizing the LC parameters, the impedance of the second harmonic is close to the short-circuit point of the Smith chart at the high frequency of the power amplifier. This method can significantly improve the working efficiency of the amplifier at the high frequency, so that the PAE of the power amplifier can be maintained at a high efficiency level over the whole working frequency band. Second, the third-stage matching circuit should satisfy the best efficiency impedance matching of the second-stage transistor. Third, the gate width of the second-stage transistor needs to be selected reasonably to provide enough driving power for the last-stage transistor without deep compression, so as to provide enough driving power margin within the working bandwidth of the power amplifier.

The total gate width of the output-stage transistor is 5.12 mm, the total gate width of the second-stage transistor is 1.92 mm, and the total gate width of the

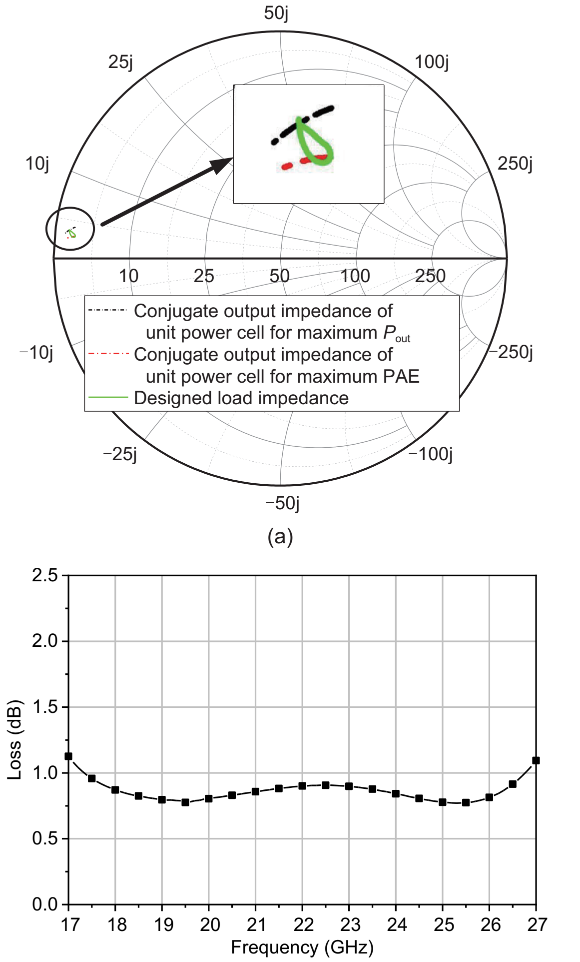

Fig. 3 The simulation results of the output matching network in the Smith chart (a) and output matching loss in the Cartesian coordinate system (b)

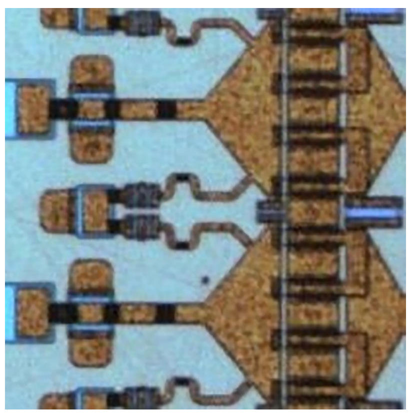

Fig. 4 Series LC resonant network

first-stage transistor is 0.8 mm. Fig. 5 shows a photo of the power amplifier under the microscope, and the size of the total amplifier is 4.2 mm×3.0 mm.

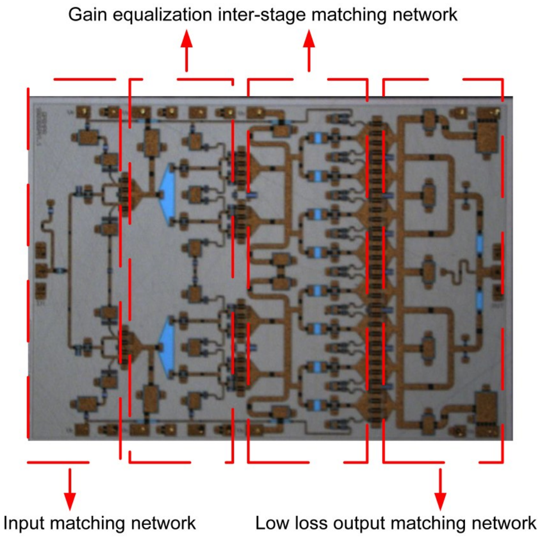

Fig. 5 Photo of the power amplifier under the microscope

3 Simulation and measurement results

According to the above theory and design method, the broadband power amplifier was manufactured and finally measured in the cavity. The measurement cavity was processed by oxygen-free copper. The amplifier was soldered to 0.2 mm Mo-Cu carrier plates for testing. To make the amplifier work in the optimal and stable state and have a suitable gain, the static operating point of the amplifier was $V_{gs}=-2$ V, V_{ds}=20 V. The test system included an E8257D PSG analog signal generator, an N6705C DC power analyzer, and an N1912A power meter. Fig. 6 shows a photo of the power amplifier installed in a metal cavity.

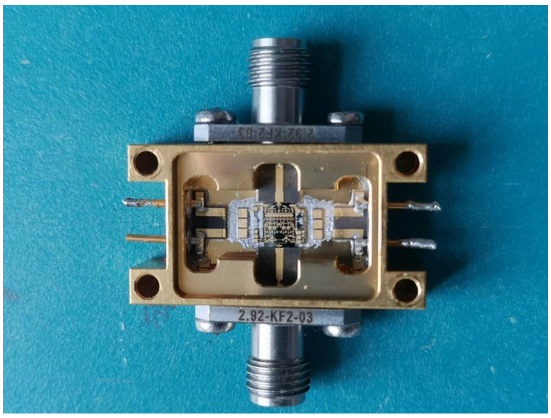

Fig. 6 Photo of the power amplifier installed in a metal cavity

The simulation and measurement results of small signal characteristics are shown in Fig. 7. The measured small signal gain was over 24 dB in the frequency range of 17–26.5 GHz, and the input voltage standing wave ratio was less than 2.2.

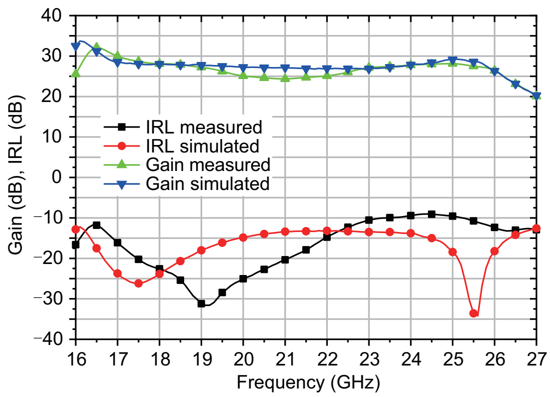

Fig. 7 The simulation and measurement results of small signal characteristics (IRL: input return loss)

Fig. 8 shows the large signal response of the broadband power amplifier measured under the CW. The saturated output power was over 42.5 dBm in the frequency range of 17–26.5 GHz, and the average PAE was 30%. The output power flatness was less than 1.0 dB.

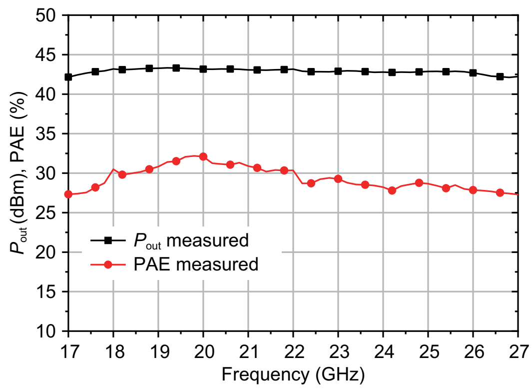

Fig. 8 The measurement results of large signal characteristics

Table 2 shows the performance comparison of the power amplifier described in this paper with the K-band broadband power amplifier in the literature or mainstream products. It can be seen that the power amplifier designed in this study had the widest band and the largest output power, and that the average efficiency of the whole frequency band reached 30%. This offers advantages in terms of comprehensive performance.

Table 2 Performance comparison of power amplifiers

Reference	Frequency (GHz)	P_{out} (dBm)	PAE (%)	Size (mm^2)
Duffy et al., 2019	18.5–24	36.5	28–40	8
Din et al., 2017	17.2–20.2	40.0	38.0	–
Northrop Grumman, 2015	18–23	38.5	30–35	10
Qorvo, 2016	17–20	40.0	26–35	8.3
This work	17–26.5	42.5	27–32.1	12.6

4 Conclusions

In this study, a GaN power amplifier with wide bandwidth, high power, and high efficiency is proposed. Low loss output stage matching circuit topology and appropriate harmonic control are adopted to improve the power amplifier efficiency at high frequency and to realize high efficiency and high power in 17–26.5 GHz; an appropriate inter-stage matching network is used to compensate for the gain roll-off effect of the transistor and to improve the gain flatness in 17–26.5 GHz. Results show that the power amplifier has over 42.5 dBm saturated output power in the frequency range of 17–26.5 GHz, with a maximum PAE of 32.1%. The output power flatness is better than 1.0 dB. In comparison with the state-of-the-art power amplifiers, this power amplifier achieves the optimal comprehensive performance.

Contributors

Ming LI designed the research. Ming LI and Quan ZHENG processed the data. Ming LI drafted the paper. Quan ZHENG helped organize the paper. Zhiqun LI, Lanfeng LIN, and Hongqi TAO revised and finalized the paper.

Compliance with ethics guidelines

Ming LI, Zhiqun LI, Quan ZHENG, Lanfeng LIN, and Hongqi TAO declare that they have no conflict of interest.

References

Campbell C, Lee C, Williams V, et al., 2009. A wideband power amplifier MMIC utilizing GaN on SiC HEMT technology. *IEEE J Sol-State Circ*, 44(10):2640-2647. https://doi.org/10.1109/JSSC.2009.2026824

Chen K, Peroulis D, 2011. Design of highly efficient broadband class-E power amplifier using synthesized low-pass matching networks. *IEEE Trans Microw Theory Techn*, 59(12):3162-3173. https://doi.org/10.1109/TMTT.2011.2169080

Dai ZJ, He SB, You F, et al., 2015. A new distributed parameter broadband matching method for power amplifier via real frequency technique. *IEEE Trans Microw Theory Techn*, 63(2):449-458. https://doi.org/10.1109/TMTT.2014.2385087

Din S, Morishita AM, Yamamoto N, et al., 2017. High-power K-band GaN PA MMICs and module for NPR and PAE. Proc IEEE MTT-S Int Microw Symp, p.1838-1841. https://doi.org/10.1109/MWSYM.2017.8059010

Duffy MR, Lasser G, Nevett G, et al., 2019. A three-stage 18.5–24-GHz GaN-on-SiC 4 W 40% efficient MMIC PA. *IEEE J Sol-State Circ*, 54(9):2402-2410. https://doi.org/10.1109/JSSC.2019.2924087

Komiak JJ, Chu K, Chao PC, 2011. Decade bandwidth 2 to 20 GHz GaN HEMT power amplifier MMICs in DFP and No FP technology. Proc IEEE MTT-S Int Microw Symp, p.1-4. https://doi.org/10.1109/MWSYM.2011.5972561

Millán J, Godignon P, Perpiñà X, et al., 2014. A survey of wide bandgap power semiconductor devices. *IEEE Trans Power Electron*, 29(5):2155-2163. https://doi.org/10.1109/TPEL.2013.2268900

Mishra UK, Shen L, Kazior TE, et al., 2008. GaN-based RF power devices and amplifiers. *Proc IEEE*, 96(2): 287-305. https://doi.org/10.1109/JPROC.2007.911060

Northrop Grumman, 2015. APN149, 18–23 GHz GaN Power Amplifier Datasheet. https://www.northropgrumman.com/wp-content/uploads/Microelectronics-APN149.pdf

Qorvo, 2016. TGA4548, 17–20 GHz 10 Watt GaN Power Amplifier Datasheet. https://www.qorvo.com/products/p/TGA4548

Xia J, Zhu XW, Zhang L, 2014. A linearized 2–3.5 GHz highly efficient harmonic-tuned power amplifier exploiting stepped-impedance filtering matching network. *IEEE Microw Wirel Compon Lett*, 24(9):602-604. https://doi.org/10.1109/LMWC.2014.2324752