Eighty nine-watt cascaded multistage power amplifier using gallium nitride-on-silicon high electron mobility transistor for L-band radar applications

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Abstract
This work presents a gallium nitride (GaN) high electron mobility transistor (HEMT)–based cascaded multistage power amplifier (MPA) in class-AB for L-band radar applications. The purpose of this endeavour is to develop an MPA using GaN HEMT devices to achieve optimised parameters such as high gain, high power, better efficiency, and linearity in a compact size. In an MPA design with multiple stages, oscillations are common owing to unwanted high gain at the lower frequency range. To overcome this issue, we introduced interstage harmonic termination networks as a novel approach to suppress high gain at low frequencies, which are prone to oscillations. The proposed cascaded MPA provides the maximum radio-frequency output power of 89 W and a power gain of 52 dB with an associated power-added efficiency of 51%. Second and third harmonic levels are −32.5 and −37 dBc, respectively. Two-tone measurements are performed with a frequency separation of 10 MHz, and an intermodulation level of less than −33 dBc is achieved.

1 | INTRODUCTION

Power amplifiers (PAs) are widely used in wireless communication and radar applications. Microwave frequencies (UHF, L-band, S-band etc.) have a dominant role in commercial and defence applications. Modern communication standards such as GSM, CDMA, W-CDMA, and WiMAX with digital modulation schemes, such as QAM, QPSK, DQPSK, OFDM, are characterised by varying signal envelopes with a high peak-to-average power ratio [1, 2]. To fulfil the requirements of communication standards, PA design includes the frequency of operation, output power, bandwidth, efficiency, gain, linearity, and cost. However, it is challenging to achieve optimum values of all parameters simultaneously [3, 4]. Therefore, trade-offs must be made, and a subset of the desired parameters can be satisfied depending on the specific needs of the application. Some traditional trade-offs are gain versus bandwidth, operating frequency versus output power, and linearity versus efficiency [4]. In wireless communication, PA has the main role of amplifying the desired modulated signal before transmission [5]. Thus, multistage PAs (MPAs) are designed to accomplish the need for a link with high gain and high output power. In MPA design, a critical concern is the possibility of oscillations caused by instabilities including very high gain, positive feedback, resonant tanks, poor isolation between DC and radio-frequency (RF) paths, and parametric oscillations of nonlinear capacitances. These instabilities are particularly worse at lower frequencies owing to high gain, and detection to avoid such oscillations is always tedious [5, 6].

Gallium nitride (GaN), a wideband gap semiconductor, has emerged as a potential candidate to fulfil the requirements of current and future communication systems [7, 8]. GaN high electron mobility transistor (HEMT)-based PAs provide a better trade-off with high output power with a compact size, owing to their high output power densities, compared with travelling wave tube amplifiers [9]. Gurdal et al. demonstrated GaN-based PAs for space applications [10]. Similarly, Cankaya et al. reported 20 W X-band PA monolithic microwave integrated circuits (MMICs) with a power gain of 27 dB using 0.25-μm GaN-on-SiC HEMT technology [11].

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We present the cascaded MPA in class AB using GaN HEMT devices for L-band radar applications. We used Nitronex (now part of MACOM) GaN HEMT devices. The capability of Nitronex GaN HEMT epi wafer technology is attributed to the development of novel transition layers that accommodate stresses originating from differences in properties of Si substrates and GaN materials. Hence, GaN-on-Si HEMT devices offer high power performance, ideally suited for inexpensive RF circuits [4]. In this work, we used a nonlinear model of Nitronex devices to extract optimum impedances for output power [12]. Section 2 highlights the design aspects of MPA including amplifiers, a power divider/combiner, and harmonic termination networks (HTNs), whereas Section 3 shows the realization and evaluation of the proposed cascaded MPA. The HTN technique is introduced as an approach to suppressing low-frequency oscillations. A conclusion is provided in Section 4.

2 | DESIGN ASPECT OF CASCADED MULTISTAGE POWER AMPLIFIER

The proposed MPA consists of four cascaded stages, as shown in Figure 1. The ultimate goal is to achieve more than 80 W output power with a gain of up to 50 dB. The proposed design consists of gain block, pre-, driver, and high-PA (HPA) stages. The first three stages are cascaded directly, whereas HPA is integrated with a power divider/combiner to enhance output power up to the desired level. The proposed MPA design consists of subsections:

i. Individual amplifiers
ii. Power divider/combiner
iii. Cascaded MPA
iv. HTNs
v. Power supply unit

2.1 | Design and development of individual amplifiers

To design the MPA, Advanced Design System (ADS) software from Keysight Technologies is used. Amplifiers are designed in class AB at the centre frequency of 1.3 GHz with a bandwidth of 100 MHz (1275–1375 MHz). For printed circuit board (PCB) development, Roger substrate TMM10i (H = 60 mil;
$\varepsilon_r = 9.8$) is selected to achieve the desired electrical lengths in a compact size. The design procedure implemented (except for gain block) is:

- Device selection
- DC analysis (for the quiescent point)
- Stability analysis and bias networks
- Extraction of source and load impedances
  - Operating power gain method, or
  - Load/source pull analysis
- Small and large signal analysis
- Optimization techniques, if required
- Layout generation

The design and development of each amplifier stage are summarised in the following sections.

### 2.1.1 | Gain block (first stage)

An MMIC of Hittite technologies (HMC479) is selected as a gain block. The key advantage is internal matching; therefore, coupling is selected according to the desired frequency with low equivalent series resistance and high self-resonance frequency along with a 50-$\Omega$ microstrip line. The bias network consists of a $\lambda/4$ transmission line and bypass capacitors, as shown in Figure 2.

The fabricated amplifier is characterised using a vector signal generator (VSG) and spectrum analyser (SA). The obtained results are shown in Figure 3, which indicates that the power gain and 1-dB compressed output power ($P_{1\text{dB}}$) are 12.8 dB and 16.5 dBm, respectively.

### 2.1.2 | Preamplifier (second stage)

This is designed using a GaN HEMT from Nitronex (NPTB-00004). To operate in class AB, the quiescent-point (Q-point) is determined by DC analysis with a drain-source current ($I_{ds}$) of 50 mA, as shown in Figure 4.

Then, a stability analysis of the transistor is performed using S-parameters. A hybrid stabilising network with a shunt resistor of 220 $\Omega$ (Rs2) and a parallel RC circuit (Rs1 and Cs) is implemented to ensure the unconditional stability of the transistor. The schematic of the preamplifier is shown in Figure 5.

After the stability analysis, small signal simulations of the transistor with the stability network are performed to observe the maximum available gain ($G_{\text{max}}$) and S-parameters, as shown in Figure 6a. The $G_{\text{max}}$ of the network is 20.4 dB, whereas the small signal gain ($S_{21}$) is 15 dB with no matching network. This shows that the transistor can be matched to have a gain as high as $\sim$19.5 dB, considering $\sim$1 dB loss. To extract the optimum load and source impedances, the operating power gain ($G_p$) of the transistor is investigated, as shown in Figure 6b. To achieve a $G_p$ of 18.5 dB, the optimum load impedance should be 37.13 + j26.19 $\Omega$. For optimum source impedance, the conjugate matching is performed, using the relation:

$$\Gamma_S = \text{conjugate of } \Gamma_{in} \quad (1)$$

where:

$$\Gamma_{in} = S_{11} + (S_{21}S_{12}\Gamma_L)/(1 - S_{22}\Gamma_L) \quad (2)$$

From Equations (1) and (2), the corresponding source impedance is 12.64 - j11.58 $\Omega$. L-type hybrid matching networks are used to transform the impedances, where source and load matching networks include lumped components (TL, $C_m$, and $L_m$-stub, respectively). The electrical lengths of TL and stub are 12.36 and 29.47 degrees, respectively.

In an amplifier design, bias networks are also important to avoid the possibility of oscillation and interference. Therefore, RF chokes of $\lambda/4$ microstrip lines are designed with high
impedances at ~92 Ω. The inductances of λ/4 microstrip lines are also calculated and replaced by inductors (Ls2 and Ls3) to reduce the PCB width. Furthermore, decoupling capacitors banks (Cb1, Cb2, and Cb3) and (Cb4, Cb5, and Cb6) are implemented at both the gate and drain bias networks, as shown in Figure 5. The preamplifier is simulated with matching and biasing networks. It is fabricated with the rest of the circuit. The simulation and measurement results of gain (G), P1dB, and power-added efficiency (PAE) are given in Figure 7. Although there is a slight variation in simulated and measured results, the obtained results still show good agreement and validate the design approach.

2.1.3 | Driver amplifier (third stage)

To meet the input requirements of the HPA, a driver amplifier is designed to achieve P_out ≥ 39 dBm with G ≥ 12 dB. High power is targeted with a 10-dB back-off for better linearity. The nonlinear model of GaN HEMT (NPTB00025) of Nitronex is used. Q-point is selected at I_dq = 125 mA (Vgs = −1.5 V). λ/4 microstrip lines along with decoupling capacitors are used to bias both the gate and drain.

A schematic of the driver amplifier is shown in Figure 8, where the stability is achieved through an RC parallel network at the gate. L-type hybrid networks are implemented at both the input and output for matching. In these networks, the electrical lengths of TLin and TLout are 4 and 13.31 degrees, respectively, whereas TLb1 and TLb2 are 90 degrees each. After the schematic design, one-tone harmonic balance (HB) simulations are performed to evaluate G, P1dB and PAE. After fabrication on a similar Roger substrate (TMM10i), large signal measurements of driver amplifier are performed. The measurement results are plotted together with the simulation results in Figure 9. The measured G, P1dB, and PAE are 12.6 dB, 41.7 dBm, and 56%, respectively. The variation in simulated; the measured results may result

FIGURE 6 Simulated results of preamplifier. (a) S-parameter analysis, (b) Gp and load stability circles

(b)

FIGURE 7 Simulated and measured results of preamplifier. (a) Gain and Pout; (b) PAE
from the layout effects, components behaviour, or LPKF machine tolerance. The results still closely match the simulations.

2.1.4 | High-power amplifier

In an HPA design, the large signal technique is used with a nonlinear model of GaN HEMT (NPTB-00,050) of Nitronex to attain the maximum output power. From DC analysis, a class AB bias point is chosen at \( I_{\text{dc}} = 240 \, \text{mA} \) \( (V_{\text{gs}} = -1.5 \, \text{V}) \). Here, stability is achieved through a bias resistor (Rb) and impedance matching networks, using the same technique implemented in published GaN MMICs [13]. Load- and source-pull simulations are performed to extract optimum impedances at the desired frequency (1.3 GHz). The extracted source impedance is \( 3.16 - j20.42 \, \Omega \), and it provides an output power of 45.5 dBm with PAE of 59\%. Similarly, a load-pull analysis is performed and the extracted load impedance is \( 14.18 - j12.29 \, \Omega \) [14]. To transform the extracted impedences, an L-type matching network (Lm and Cm) is used at the input whereas the balanced stub method is implemented at the output. The electrical length of each stub is 38.36 degrees, and it is 90 degrees for \( \lambda/4 \) transmission lines (TL1 and TL2). The schematic of the HPA is shown in Figure 10.

From the HB simulation, \( P_{\text{1dB}}, \, \text{G} \) and \( \text{PAE} \) are achieved as 45.8 dBm, 15.3 dB and 69\%, respectively, as shown in Figure 11. After fabrication, HPA is characterised with state-of-the-art RF instruments using the setup shown in Figure 12. The measured results of \( P_{\text{1dB}}, \, \text{G} \) and \( \text{PAE} \) are 45.5 dBm, 13.5 dB, and 63\%, respectively, as given in Figure 11. The slight variation between the simulation and measurement results observed may be due to heating issues, because HPA is characterised on a metallic (aluminium) plate, which was not dissipating heat adequately. In the proposed MPA, two HPAs are used in parallel to enhance the output power with the designed power divider/combiner.

2.2 | Power divider/combiner

To attain high output power in the proposed MPA, a 3-dB Wilkinson power divider (WPD) approach [15–17] is implemented to handle output power up to 100 W. The schematic of
the WPD is demonstrated in Figure 13, where 100 Ω is used between two quarter wave transmission lines \((Z_1 = Z_o \sqrt{2})\).

S-parameter analysis is performed by simulation; the results are given in Figure 14. Reasonable insertion losses \((S_{21}, S_{31})\) of −3.1 dB are achieved with an isolation \((S_{32})\) less than −35 dB at 1.3 GHz. Similarly, the return losses \((S_{11}, S_{22}, S_{33})\) are −30 dB or less. The measurements are also taken after the fabrication of WPD (shown in Figure 20). They indicate
similar results with the simulation, in which $S_{21}$ and $S_{31}$ are $-3.3$ and $-3.26$ dB, respectively, with an isolation ($S_{32}$) of 31 dB.

2.3 | Cascaded MPA

The designed blocks of individual amplifier stages and power divider/combiner are cascaded to realize an MPA in ADS software, where the schematic is similar to Figure 1 except for the circulator and the antenna. S-parameter analysis is performed from 200 MHz to 2.0 GHz; the results are given in Figure 15.

![Figure 15](image)

**Figure 15** Simulated S-parameters of a cascaded multistage power amplifier

The simulation shows a small signal gain ($S_{21}$) of 63 dB at 1.3 GHz, whereas the $\mu$-factor is above 1 throughout the whole simulation band. However, high value of $S_{21}$ of 75 dB is also observed at the lower frequency band. It indicates a high risk of instability that can affect the performance of the cascaded MPA. Therefore, to avoid the possibility of oscillations, HTNs are implemented as a novel approach between the amplifier stages.

2.3.1 | Harmonic termination networks

This HTN technique is implemented among the amplifier stages to reduce the gain at the lower frequency band. Moreover, stability between the amplifier stages is improved owing to the suppression of the oscillations. Consequently, the cascaded MPA will prove the proposed performance without instability problems.

![Figure 16](image)

**Figure 16** Schematic of harmonic termination network

Typically, HTN circuits are used to suppress second and third harmonics of PA to increase output power, PAE, and ruggedness. [18–20]. Nikandish et al. proposed an HTN technique to suppress the even harmonics in class F PA [21]. They claimed that this technique is useful for terminating an arbitrary number of harmonics in single as well as concurrent multiband for class F PA. Similarly, Mahdi et al. proposed an HTN technique to suppress high intermodulation and demonstrated an improvement in the linearity of the amplifier without degradation of efficiency [22]. Therefore, we propose HTNs as novel approach to enhancing the performance and stability of a cascaded MPA in compact size. A schematic of an individual HTN is shown in Figure 16.

A typical HTN consists of an inductor-capacitor network that acts as a notch filter at the desired frequency. Therefore, HTNs are implemented in the proposed MPA to suppress gain at the lower frequencies from 250 to 500 MHz. Transmission lines (TL1, TL2, and TL3) are designed with a constant length and width whereas the capacitance is changed from 36 pF (HTN-1) to 27 pF (HTN-2) to suppress $S_{21}$ at out-of-band lower frequencies. The simulated and measured results are shown in Figure 17. The simulated insertion loss ($S_{21}$) of HTN-1 at the lower frequency is $-41.5$ dB whereas its impact at 1.3 GHz is only $-1.2$ dB. Similarly, insertion loss of HTN-2 is $-42$ dB and its impact at the desired frequency is only $-1.27$ dB.

The fabricated HTN-2 has an $S_{21}$ of $-36.3$ and $-1.4$ dB at 410 MHz and 1.3 GHz, respectively. The difference between simulated and measured data is only 0.13 dB. The HTN-1 is fabricated only by replacing the 36 pF capacitor by 27 pF.
and troubleshooting. The TPs are as follows: TP-1 is implemented to characterise the first two amplifier stages, TP-2 is designed as feed to the RF input of the driver amplifier as well as to characterise the HTN response (both in separate and integration configurations) whereas TP-3 is used to characterise the final stage (HPA) separately. To isolate reflections from previous amplifier stages, an isolator is also used at the input of the driver amplifier.

A small size of sequential power supply (shown in Figure 20) is also implemented as recommended for GaN HEMT devices [23]. It consists of four tuneable gate bias points. Variable resistors (trimmer) are also implemented to adjust the gate bias according to the desired Q-point of each amplifier. The dimension of proposed MPA is $190 \times 100 \times 22$ mm$^3$. After integration, the characterisation is performed as discussed subsequently.

### 3.1 Small signal analysis

Small signal measurement is performed using a performance network analyser from Keysight. It is calibrated, using E-Cal, from 600 MHz to 2.0 GHz before S-parameter analysis. The measured S-parameter results are shown in Figure 21, where $S_{21}$, $S_{11}$ and $S_{22}$ are 52.5, $-14.6$ and $-4.0$ dB, respectively. $S_{12}$ also gives the promising result of 75 dB. These results indicate a reasonable performance as desired. The bandwidth of proposed MPA is ~100 MHz.

### 3.2 Large signal analysis

This characterisation is performed in the following steps.

#### 3.2.1 One-tone analysis

It is performed to measure the output power, $G$, PAE, and harmonic distortion. A measurement setup similar to Figure 12 is used to characterise the proposed MPA. For this, a VSG from Keysight is used to sweep the input signal from $-20$ to $+2$ dBm at the desired frequency whereas the output power is measured on the SA from Keysight. A power attenuator is also used to keep RF instruments in the permissible limits.
The measured one-tone results together with simulated results are shown in Figure 22.

The measurements show a maximum output power of 49.5 dBm (89 W), whereas the simulated and measured $P_{1\text{dB}}$ results are closely matched. Similarly, the simulated and measured values of G are 57 and 52 dB, respectively. The variation in G ($\sim 5$ dB) is due to the cumulative effect of individual amplifier stages, as mentioned in the results shown in Figures 7, 9 and 11. Therefore, the input drive of the cascaded MPA is increased by 5 dBm compared with the simulation to achieve the maximum output power. Similarly, a variation in PAE is also observed owing to the change in RF input power. Moreover, power divider/combiner and interstage HTNs contribute to these variations.

Second and third harmonic levels are also measured; they are $-32.5$ and $-36.9$ dBc, respectively, as shown in Figure 23.

**FIGURE 20** Photograph of fabricated multistage power amplifier. HPA, high-power amplifier; RF, radio-frequency

**FIGURE 21** Measured S-parameters of cascaded multistage power amplifier

**FIGURE 22** Simulated and measured results of proposed multistage power amplifier: (a) Gain and $P_{\text{out}}$; (b) PAE
3.2.2 Two-tone analysis

In RF communication, odd-order intermodulation distortions (IMDs) are important because these lie near the frequency of operation and may interfere with the desired signal. In general, two-tone analysis indicates the performance of the amplifier in the presence of strong interferers. Therefore, two-tone measurement was performed with a 10-MHz separation frequency (Δf) at the desired centre frequency using VSG. The measured results are shown in Figure 24, where IMD3 is −33 dBc. The

Table 1 High-power amplifier comparison with published data

| Reference | Frequency (GHz) | Technology | Class | Pout (W) | Gain (dB) | PAE/ηD (%) |
|-----------|----------------|------------|-------|----------|-----------|-------------|
| [24]      | 1.72           | GaN        | AB    | 12.6     | ~13       | 45/60       |
| [25]      | 1–2.55         | GaN        | E     | 10       | 10        | 55/60       |
| [26]      | 1–2            | GaN        | -     | 90       | 14        | −/65        |
| [27]      | 1–2            | GaN        | AB    | 130      | 12        | 55          |
| [28]      | 1.575          | GaN        | F     | 100      | 15        | 66/−        |
| [29]      | 1.575          | GaN        | F     | 49       | 17.2      | −/47        |
| This work | 1.3            | GaN        | AB    | 46       | 15        | 63/−        |

Abbreviation: GaN, gallium nitride.
amplitudes of both left (2f₁-f₂) and right (2f₂-f₁) sides are symmetrical, which indicates that they will not affect the modulated signal during communication. Hence, an optimal performance of cascaded MPA is achieved.

3.3 | Comparison with published data

The performance of the proposed MPA is also compared with published data. In the MPA design, its performance mainly depends on the final stage of the amplifier (i.e. HPA). Therefore, we first compared the performance of HPA as shown in Table 1. The proposed HPA shows an optimal performance in terms of gain (G) and efficiency at the desired frequency of operation. We also observed that proposed HPA provided an IMD₃ level of about –33 dBc, which is good compared with Kilic and Demir [24], where the IMD₃ level is only –20 dBc.

After a comparative analysis of HPA, we compared the performance of the proposed MPA with published data, as shown in Table 2. In comparison, the results of our proposed MPA is comparable to Giofré et al. [30] except for the output power. Giofré et al. [30] developed a class F MPA at 1.25 GHz with a 24% duty cycle for pulsed radar application. This MPA has a bandwidth of ~75 MHz with dimensions of 198 × 192 × 20 mm³, whereas our proposed MPA provides 89 W CW output power at 1.3 GHz with a bandwidth of ~100 MHz, and the dimensions are 190 × 100 × 22 mm³ (45% size reduction compared to Garg et al. [31]).

Hence, the performance of the proposed MPA is credible and provides a better trade-off between output power and efficiency with the desired gain and linearity.

4 | CONCLUSION

A compact and high-performance cascaded class AB MPA is developed for L-band radar applications. In this work, GaN-on-Si HEMT devices of Nitronex are used for cost-effectiveness. To achieve an optimised output power together with high power gain, efficiency, and linearity, small signal design techniques are applied for pre- and driver amplifiers. For HPA, large signal techniques are used to ensure high output power performance. Load and source-pull methods are used using non-linear models of GaN HEMT devices to extract the optimum impedances.

In MPAs, low-frequency oscillations may occur owing to the high gain. Therefore, HTNs are introduced as a novel approach to reduce high gain at the lower frequencies. Interstage TPs are also incorporated to characterise and troubleshoot individual components. Close agreement is achieved between the simulated and measured results, which reveals that the non-linear models of HEMTs used in the design are accurate and the parasitic effects are incorporated adequately to achieve the desired results in a real scenario. The measurement results of the proposed MPA show an output power of 89 W with a gain of 52 dB, and a PAE of ~51.3% is achieved in compact size, making it a suitable candidate for L-band radar applications.

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REFERENCES

1. Tan, J., Yuk, K.S., Branner, G.R.: Design of a high power, wideband power amplifier using AlGaN/GaN HEMT. In: Proceedings of the 2017 IEEE 18th Wireless and Microwave Technology Conference (WAMICON), pp. 1–4, Cocoa Beach (2017)
2. Kosaka, N., et al.: A high efficiency GaN HEMT high power amplifier at L-band. In: Proceedings of the 2014 Asia-Pacific Microwave Conference, pp. 789–791, Sendai (2014)
3. Wiegener, D., et al.: Multistage broadband amplifiers based on GaN HEMT technology for 3G/4G base station applications with extremely high bandwidth. In: Proceedings of the European Gallium Arsenide and Other Semiconductor Application Symposium (GAAS), pp. 641–644, Paris (2005)
4. Wang, F.: Design and Analysis of High Efficiency L-band Power Amplifiers. PhD thesis. California Institute of Technology, Pasadena (2006)
5. Wei, Y., Yie, T.S., Hia, C.G.: Design of X-Band High Power Cascade Amplifier. High Freq. Electron. Technical report 6(1), 24–32 (2007)
6. Aanakabe, A., et al.: Detecting and avoiding odd-mode parametric oscillations in microwave power amplifiers. Int J RF Microw. Computer-Aided Eng 15(5), 469–478 (2005)
7. lee, H.: Presentation on amplifier design in ADS for radar applications. In: Proceedings of the Aerospace and Defense Symposium, California USA (2005). read.pudn.com/downloads154/ebook/682565/功率放大器的设计.pdf
8. Azam, S.: Microwave Power Devices and Amplifiers for Radars and Communication Systems. PhD thesis. Linköping University, Sweden (2009)
9. Osuma, K., et al.: Over 74% efficiency, L-band 200W GaN-HEMT for space applications. In: Proceedings of the 2016 46th European Microwave Conference (EuMC), pp. 397–400, London (2016)
10. Gundal, A., et al.: X band GaN based MMIC power amplifier with 36.5dBm P1-dB for space applications. In: Proceedings of the 2018 48th European Microwave Conference (EuMC), pp. 1313–1316, Madrid (2018). https://doi.org/10.23919/EuMC.2018.8541703
11. Akoglu, B.C., et al.: GaN based driver and power amplifier MMICs for X-band transceiver modules. In: Proceedings of the 2019 IEEE 19th Mediterranean Microwave Symposium (MMS), pp. 1–4, Hammamet (2019). https://doi.org/10.1109/MMS48040.2019.9157248
12. Ozpineci, B., Tolbert, L.M.: Comparison of Wide-Bandgap Semiconductors for Power Electronics Applications, United States. 12 Dec (2003). https://doi.org/10.2172/865849
13. Zafar, S., et al.: GaN based LNA MMICs for X-band applications. In: Proceedings of the 2020 17th International Bhurban Conference on Applied Sciences and Technology (IBCAST), pp. 699–702, Islamabad (2020). https://doi.org/10.1109/IBCAST47879.2020.9044560
14. Hayat, K., et al.: High performance GaN HEMT class-AB RF power amplifier for L-band applications. In: Proceedings of the 2013 10th International Bhurban Conference on Applied Sciences & Technology (IBCAST), 389–392, Islamabad (2013)
15. Gonzalez, G.: Microwave Transistor Amplifiers Analysis and Design, 2nd edn. Prentice Hall, New Jersey (1997)
16. Grebennikov, A.: Power combiners, impedance transformers and directional couplers: part II. High Freq. Electron. report 7(1), 42–54 (2008)
17. Pozar, D.M.: Microwave Engineering, 3rd ed. John Wiley, Inc, Hoboken (2007)
18. Spirito, M., et al.: Power amplifier PAE and ruggedness optimization by second-harmonic control. IEEE J. Solid State Circ. 38(9), 1575–1583 (2003)
19. Chung, Y., et al.: Effects of output harmonic termination on PAE and output power of AlGaN/GaN HEMT power amplifier. IEEE Microw. Wireless Compon. Lett. 12(11), 421–423 (2002)
20. Gao, S., et al.: High-efficiency power amplifier design including input harmonic termination. IEEE Microw. Wireless Compon. Lett. 16(2), 81–83 (2006)
21. Nikandish, G., Babakprur, E., Medi, A.: A harmonic termination technique for single- and multi-band high-efficiency class-F MMIC power amplifiers. IEEE Trans. Microw. Theor. Tech. 62(5), 1212–1220 (2014)
22. Mahdi, A.E., Sobih, A.G., El-Kafafi, M.A.: Design and implementation of 10W, highly linear, wideband and efficient power amplifier using harmonic termination. In: Proceedings of the 2016 IEEE Middle East Conference on Antennas and Propagation (MECAP), 1–4, Beirut (2016)
23. Cheema, N., et al.: Design and implementation of bias sequence circuits for GaN HEMT amplifiers both pulsed and CW applications. In: Proceedings of 2015 10th International Bhurban Conference on Applied Sciences & Technology (IBCAST), 420–423, Islamabad (2013)
24. Kilic, H.H., Demir, S.: Highly efficient dual-band GaN power amplifier utilising pin diode tunable harmonic load matching. IET Microw. Antennas Propag. 13(1), 63–70 (2019)
25. Moloudi, F., Jahanirad, H.: Broadband class-E power amplifier design using tunable output matching network. AEU-Int. J. Electron. Commun. 118, 153142 (2020)
26. Cipriani, E., et al.: A highly efficient octave bandwidth high power amplifier in GaN technology. In: Proceedings of the 2011 6th European Microwave Integrated Circuit Conference, pp. 188–191, Manchester (2011)
27. Rochette, S., et al.: A high efficiency 140W power amplifier based on a single GaN HEMT device for space applications in L-band. In: Proceedings of the 2012 7th European Microwave Integrated Circuit Conference, pp. 127–130, Amsterdam (2012)
28. Wu, H., Yuk, K.S., Branner, G.R.: A compact 100W, 68% class F GaN power amplifier for L-band GPS. In: Proceedings of the 2019 IEEE 20th Wireless and Microwave Technology Conference (WAMICON), pp. 1–4, Cocoa Beach (2019). https://doi.org/10.1109/WAMICON.2019.8765474
29. Wu, H., et al.: High power class F GaN HEMT power amplifier in L-band for global positioning systems application. In: Proceedings of the 2018 IEEE 19th Wireless and Microwave Technology Conference (WAMICON), 1–4, Sand Key (2018). https://doi.org/10.1109/WAMICON.2018.8363920
30. Giofré, R., et al.: A GaN high power and efficient amplifier for L-Band Galileo system. In: Proceedings of the 2015 Integrated Nonlinear Microwave and Millimetre-wave Circuits Workshop (INMMiC), pp. 1–3, Tsorrima (2015)
31. Garg, S.K., Aich, S., Dhar, J.: GaN based L-band high power and high efficiency pulsed transmitter. In: Proceedings of the 2015 IEEE MTT-S International Microwave and RF Conference (IMaRC), pp. 155–158, Hyderabad (2015)
32. Amiri, M., Alekajbaf, Y., Mssoumi, N.: L-band power amplifier design with discrete GaN transistor. In: Proceedings of the Iranian Conference on Electrical Engineering (ICEE), Mashhad, pp. 311–314 (2018)
33. Nakaede, K., et al.: Development of 150W S-band GaN solid state power amplifier for satellite use. In: Proceedings of the 2010 Asia-Pacific Microwave Conference, pp. 127–130, Yokohama (2010)

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