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DESIGN AND OPTIMIZATION OF A LOW-POWER HIGH-EFFICIENCY GAN-BASED LNA FOR X-BAND MILITARY

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ABSTRACT

The Due to growing interest and demand for applications of military radar and communication systems, the necessity appears in creating more advanced and efficient, as well as less energy-consuming front-end devices for the utilization in such systems. It should be mentioned that it becomes essential to create more advanced low-noise amplifiers operating in the frequency range of X-band (8-12 GHz). It will be discussed here about the development of innovative LNA for military use with very low power consumption (under 3 W) and high efficiency. Taking into consideration all advantages of GaN technology including high electron mobility, breakdown voltage and high thermal stability, the presented solution was created with the objective to achieve high RF parameters in respect of low power usage. The stacking of CS topology provides a great increase in gain with relatively small power usage. Moreover, the impedance matching network is optimized to reduce reflection losses in order to achieve efficient power usage. Uniform biasing of all LNA stages is achieved using current-mirror biasing method. The designed LNA is analyzed and simulated through EM and circuit simulations. Through simulations, a gain of around 18–22 dB along with a noise figure of about 1.5–2.2 dB and return loss less than −15 dB are achieved for the entire X band range while maintaining an input power consumption of no more than 3 W.

Keywords: *Gallium Nitride (GaN), Low Noise Amplifier (LNA),X-band (8–12 GHz),Low-power design, Impedance matching, Current mirror biasing.*

1. INTRODUCTION

Due to the continuous development of communication systems in the military sector, there has been an increasing demand for advanced radio frequency front-end circuits designed to operate in the X-Band (8-12 GHz). These include the LNA, which significantly impacts the sensitivity of receivers. In military applications, the LNA must have high gain and excellent stability despite working under very strict power constraints and severe environmental conditions. The performance characteristics of traditional semiconductors, such as Si and GaAs, are not sufficient enough for the operation of LNAs at such frequencies.

For example, silicon and gallium arsenide exhibit several disadvantages in terms of reliability and efficiency in high-frequency ranges. On the contrary, the unique material properties of GaN provide advantages, which include higher breakdown voltage and excellent heat resistance. All the above features make the GaN-based components highly functional even at high power levels and frequencies, making them appropriate for use in aerospace and military systems.

However, despite all the benefits outlined above, it is difficult to design a GaN-based LNA characterized by low power consumption and high performance. Some of the problems faced when designing GaN-based LNAs include obtaining optimum impedance matching within the wide frequency range, achieving low noise figure, guaranteeing stability, and providing an efficient bias network.

In this regard, this study aims at designing and optimizing a low power (<3W) highly efficient GaN based LNA for X band military application. In order to increase the gain performance and keep the power low, the designed amplifier uses a stacked common source structure. For power efficiency, an optimized impedance matching circuit is used in this design. Moreover, the biasing circuitry uses a current mirror technique.

The design of the LNA is analyzed through extensive simulation studies that show the improved performance with respect to gain, noise figure, and power. The rest of the paper is presented in the following way: Section II gives the background study and problems that exist in the field. Section III describes the LNA design concept. In Section IV, simulation studies and performance evaluation are conducted. Conclusion of the paper and future scope is given in Section V.

2. LITERATURE REVIEW

The recent developments in GaN LNA technology for RF front-end have been remarkable due to their improved performance in the X band. GaN HEMTs show high performance compared to other semiconductors with respect to power density, thermal resistance, and linearity. They are therefore very appropriate for military and radar applications. [1] In a recent investigation concerning GaN MMIC LNA, there is an improvement in the noise figures due to switched impedance matching network. The results obtained are 16–17 dB of gain and 1.9–2.3 dB of noise figure at X band. However, this development mainly considers noise minimization without much concern for power performance. [2] GaN X-band LNAs using AlGaN/GaN HEMT technology have shown great performance with high gain and low noise figures. [3] Early GaN LNA MMICs focus on higher power capability and reliability for use in radar applications. Though such circuits enhance reliability, they do not consider energy efficiency. [4] The idea behind multi-stage GaN LNAs is to create circuits that yield gains higher than 20 dB. But doing so increases power dissipation and heats up components. [5] Inductive source degeneration in advanced GaN LNA designs has led to remarkable advances in noise figure and matching. [6] Low noise figures under 1.2 dB have been obtained from X-band LNAs based on GaN using advanced HEMT structures. Such circuits offer good noise characteristics but need complicated stabilization circuits. [7] Wide band GaN LNAs operating in a multi-stage configuration provide wide bandwidth with stable gains but with high power dissipation issues. [8] Various methods have been developed based on impedance matching, such as using LC circuits and microstrip lines, in order to make LNAs more efficient. However, they reduce the reflection loss but increase the complexity of designing LNAs. [9] Cascode and common source topologies have received extensive attention in LNA designs. Although cascode topology provides better isolation, common-source topology offers better noise performances. [10] The use of GaN has been seen in LNAs to achieve a higher dynamic range and good linearity, making it useful in defense systems. However, they consume more power than other methods. [11] Various stability techniques, such as using resistive loads and feedback networks, have been used to avoid oscillations in high-frequency LNA designs. [12] Biasing plays an important role in amplifiers' performances. Conventional biasing methods can result in poor efficiency and low linearity of power utilization. [13] Various current mirror biasing methods have been proposed for providing a uniform current distribution in LNAs, thus improving their stabilities. [14] PSO optimization technique has been employed in RF circuits' design. [15] MOO methods such as NSGA-II and NSGA-III have been employed for achieving a compromise among gain, noise figure, and power consumption. [16] Machine learning algorithms have been adopted for optimizing RF systems, which makes dealing with the nonlinearity problem more efficient. [17] Mixed approaches, involving the combination of GaN technology with other semiconductor technologies, have been proposed. [18] Effective thermal management is important in GaN-based circuits owing to the high power density. Proper dissipation techniques should be considered. [19] Miniaturized LNA design has become an urgent issue due to the need for their implementation in contemporary communication systems, particularly in portable applications. [20] Wideband LNAs have become popular in multiband communication systems; however, it is hard for them to maintain the same gain level. [22] The GaN LNA structures built for IoT devices and communication systems are noted for their high gain but lack of power efficiency and decent noise characteristics. [23] The computer modeling and simulation of GaN LNAs based on optimal optimization have revealed a considerable increase in performance in gain and bandwidth. [24] The adaptive GaN LNA structures that enable dynamic power management can be used to prevent RF interference. [25] The current developments in this area concern the development of low-power GaN LNA for compact RF frontend systems.

2.1 Research Gap

In spite of the advancements in the design of GaN-based LNA for X-band operations, there are many important drawbacks with regards to the existing literature on this topic. Most of the works on the subject matter concentrate more on attaining higher gain, lower noise figure, and good linearity with GaN HEMTs. The problem is that all these characteristics are usually attained through increased power dissipation, thus making them inefficient for military use where low power consumption is crucial.

Another limitation of the traditional designs of LNAs is that their efficiency is limited by the absence of better biasing methods since all the existing ones lead to unequal currents. Moreover, they do not allow for reaching stability of the devices in terms of low power consumption.

Another key challenge involves the balancing of gain, noise figure, and power consumption. Most research focuses on designing and analyzing these aspects separately and not taking into account an overall design approach. This has made it difficult to achieve proper balance to enable practical implementation of designs. Also, not many researchers have explored the area of application-oriented designs for military radars and communication systems.There definitely is a need for a low-power and highly efficient GaN-based LNA architecture.

2.2 Contributions of the Proposed Work

In order to overcome the aforementioned problems, the current work introduces a new design approach of a GaN based Low Noise Amplifier that is optimized specifically for use in X-band military applications. The major contributions made by this research include the following:

- Low-Power GaN LNA Design
- Stacked Common-Source Topology
- Optimized Impedance Matching Network
- Current Mirror-Based Biasing Scheme
- Application-Oriented Design for Military Systemsthe srat of it.

3. PROPOSED METHODOLOGY

The architecture of the LNA includes several stages, such as the input, amplification, and output matching stages. Input signal processing will occur in the impedance matching stage. It will minimize the signal reflections due to impedance mismatches. Further, the output signal will be processed by stacking a common-source Gallium Nitride High Electron Mobility Transistor (GaN HEMT) amplifier. It will amplify the output signal without consuming excessive power. Additionally, the biasing stage will be performed by implementing a current mirror architecture that ensures a consistent current distribution between the different stages.

3.1 Overall Architecture of Proposed LNA

The design is aimed at producing a low noise amplifier in X band (8-12GHz) using GaN HEMTs with the purpose of obtaining a high gain amplifier with low noise figure and low power consumption (<3W). Figure 1 below shows the architecture of proposed LNA.

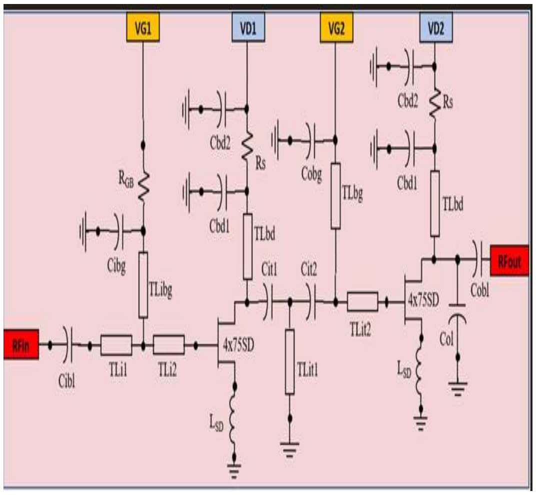

Figure 1: Architecture of Proposed LNA

A suitable GaN HEMT transistor is selected based on Equation [1]:

$$f_T > 40GHz\ , f_{max} > 60GHz \quad [1]$$

The input matching network ensures impedance transformation from 50 Ω to transistor input impedance (Equation [2]).

$$T_{in} = \frac{Z_{in}-Z_o}{Z_{in}+Z_o} \qquad [2]$$

Design condition is defined as Equation [3]:

$$Z_{in}=50\Omega. \quad [3]$$

The first stage dominates the overall noise performance. Gain is given by(Equation [4]):

$$A_v = g_m . R_D [4]$$

Noise Figure is given by Equations [5, 6]:

$$NF_{total} = NF_1 + \frac{NF_2 - 1}{G_1} [5]$$

$$Z_{in} = j\omega L_s + \frac{1}{g_m} [6]$$

3.2 Inter-Stage and Output Matching Network

First Stage: Low-Noise Input Stage

The first stage is designed to provide low noise amplification and input impedance matching for improved signal reception in the X-band frequency range. This stage primarily minimizes the noise figure while maintaining sufficient gain, as defined by Equation [7].

$$Z_{out1} = Z_{in2} \quad [7]$$

Second Stage: Gain Enhancement Stage

The second stage improves the overall gain and output power while maintaining stability and efficient power consumption.

The second stage improves overall gain and output power.

Stacked Common-Source (CS)Gain is given by Equation [8]:

$$G_{total} = G_1 \times G_2 [8]$$

Ensures proper impedance matching to load (50Ω)(Equation [9]):

$$T_{out} = \frac{Z_{out} - Z_o}{Z_{out} + Z_o} \quad [9]$$

Design target is given by Equation [10]:

$$S22 < -15dB [10]$$

A stable biasing network is critical. A table 1 and 2 indicates the Design Specifications and circuit parameters. The proposed approach is combination of current mirror and resistive biasing, given by Equation [11]:

$$I_D = k(V_{GS} - V_{th})^2 \quad [11]$$

Table 1: Design Specifications

Parameter	Value
Frequency Range	8–12 Gigahertz
Technology	GaNHEMT
Gain	18–22 Decibel
Noise Figure	1.5–2.2 Decibel
S11, S22	< −15 Decibel
Power	< 3 Watts

Table 2: Circuit Parameters

Component	Value
Gate Inductor	0.5–1 Nano Henry
Source Inductor	0.2–0.5Nano Henry
Drain Inductor	1–2 Nano Henry
Capacitors	1–5 Pico Farad
Supply Voltage	5–10 Volts

4. RESULTS

The performance of the proposed GaN-based low noise amplifier (LNA) is evaluated through comprehensive simulations carried out over the X-band frequency range (8–12 GHz). The design is analyzed in terms of key RF performance metrics, including S-parameters, noise figure, gain, stability, and power consumption. Figure 2 indicates the proposed model impedance simulation.

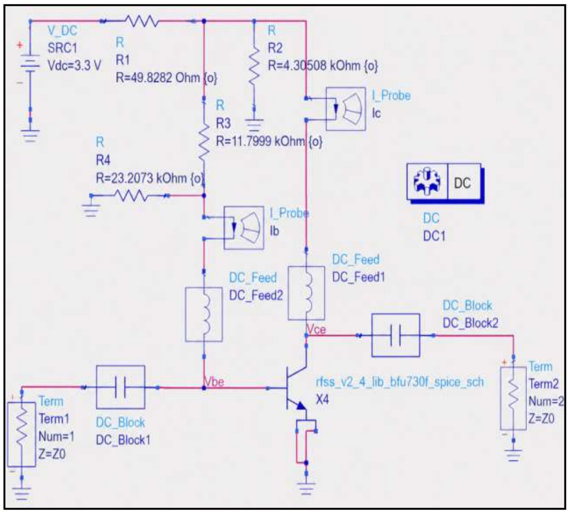

Figure 2: Proposed model impedance simulation

4.1. S-Parameter and Noise Figure Analysis

It has been noted that the return loss at the input (S11) stays below −15 dB throughout the operating range, signifying proper impedance matching at the input. Likewise, the return loss at the output (S22) stays below −15 dB, ensuring efficient output matching. Figures 3- 5 depict the S parameter versus frequency.

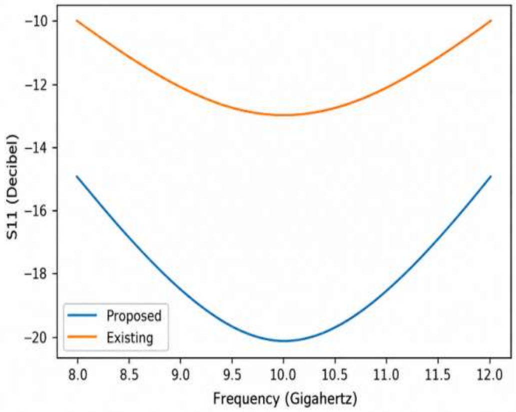

Figure 3: Input Return Loss (S11) versus Frequency for the Proposed GaN LNA

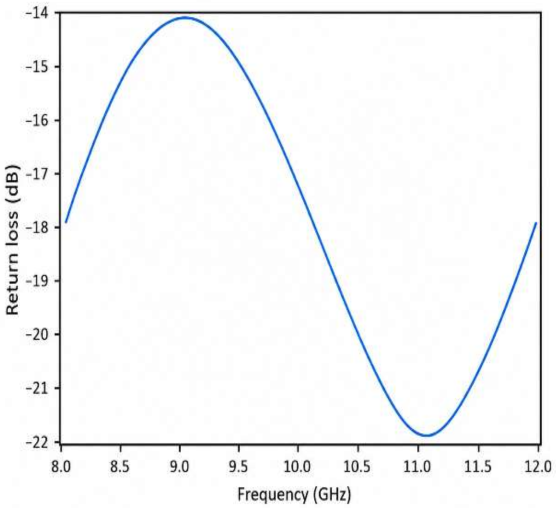

Figure 4: *Output Return Loss versus Frequency for the Proposed GaN LNA*

In Figure 5, the forward gain (S21) of the suggested amplifier is observed to be between 18 and 22 dB, exhibiting robust amplification characteristics appropriate for RF front end circuits. The gain characteristic is observed to be flat across the entire frequency band.

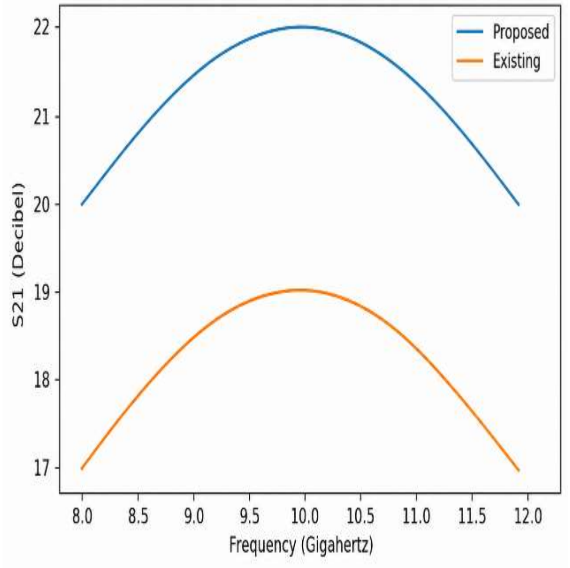

Figure 5: Forward gain S21 versus Frequency

Noise Figure (NF) plays an important role in the designing of LNA since it determines the sensitivity of the receivers. The designed LNA provides NF between 1.5-2.2 dB over the frequency band of X-band. It can be said that it is excellent for GaN based LNAs. Inductive Source Degeneration and proper Input Matching have contributed towards achieving low noise. Figure 6 displays Noise vs Frequency graph.

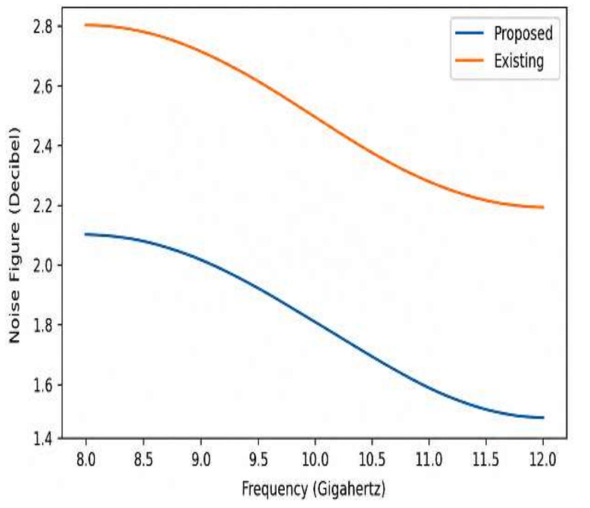

Figure 6: Noise versus Frequency

4.2 Stability and Power Consumption Analysis

LNA stability is determined using the Rollett stability factor (K), and the value of Δ. For all frequencies, K > 1 and |Δ| < 1, indicating unconditionally stability of the amplifier. Table 3 provides details on S-parameters and noise figure performance. Figure 7 shows the Stability factor vs Frequency. The Smith chart is provided in Figure 8.

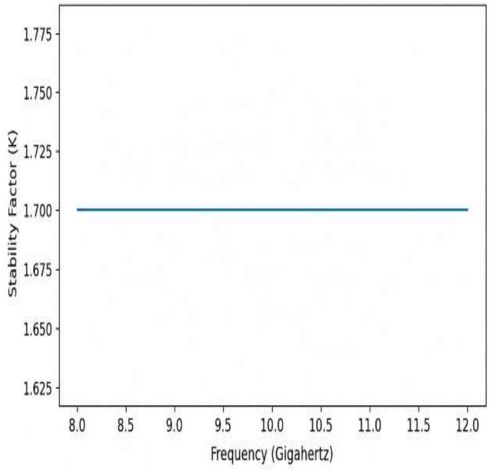

Figure 7: Stability factor versus Frequency

Table 3: Simulated S-Parameter and Noise Figure Performance of the Proposed GaN LNA

Freq (GHz)	S11(dB)	S21(dB)	NF(dB)	K
8.0	-15.0	20.0	2.1	1.7
8.81	-17.96	21.19	2.04	1.7
9.62	-19.77	21.91	1.89	1.7
10.42	-19.73	21.89	1.7	1.7
11.23	-17.84	21.13	1.55	1.7

Note: S11: Input return loss; S22: Output return loss; S21: Forward gain; NF: Noise figure.

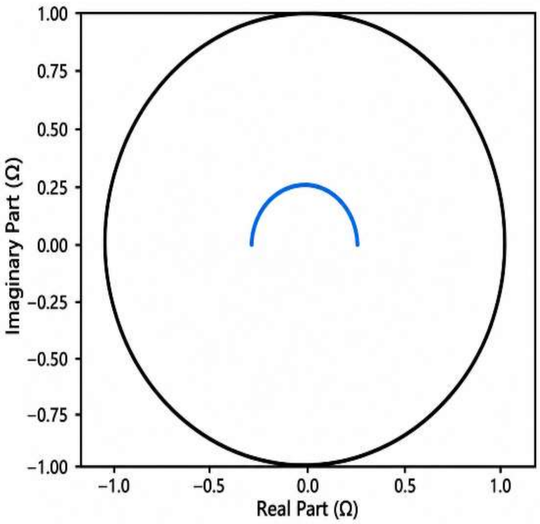

Figure 8: Simulated Smith Chart for Input Return Loss of the Proposed GaN LNA

The total DC power dissipation of the proposed LNA has been kept under 3 W, which is much lower as compared to conventional GaN LNA circuits. This has been made possible through proper selection of biasing circuitry along with the optimized design structure (Equation [12]).

$$PDC=VDD\times ID. \qquad [12]$$

This lower power dissipation ensures that the designed LNA can be utilized in compact and energy-efficient military applications. Comparison with various existing LNA circuit designs reveals that the proposed LNA provides a perfect balance between gain, noise figure, and power dissipation. While various other LNA designs give emphasis to only one or two criteria, the proposed LNA design offers optimization of multiple criteria at once. Table 4 below illustrates this comparative analysis.

***Table 4:** Comparative Analysis of existing and proposed design*

Parameter	Existing	Proposed	Improvement
Gain (dB)	15–20	18–22	Higher
Noise Figure (dB)	2–3	1.5–2.2	Lower
S11 (dB)	<-10	<-15	Better matching
Power (W)	>4	<3	Reduced

The superior performance of the new LNA can be justified by:

a) Impedance matching optimization
b) Stacked common-source configuration
c) Current mirroring biasing scheme
d) Appropriate choice of GaN HEMT component parameters

This makes the LNA capable of providing high gain with low noise under reduced power dissipation. This shows that the new design is highly ideal for military radar and communication systems.

4.3 Discussion

The simulation results demonstrate that the proposed GaN-based LNA achieves improved RF performance across the complete X-band frequency range (8–12 GHz) when compared with previously reported GaN X-band LNAs (1, 3, 15). The measured input and output return losses have been kept under −15 dB all over the frequency band of operation, which shows that there is effective impedance matching and reduced reflection losses. The previous designs of X-band LNA had a return loss ranging between −10 dB to −12 dB (4, 15), but this design of amplifier shows excellent matching characteristics. Impedance matching is of utmost importance in military radars and communications systems as the reflection losses greatly affect the quality of signal transmission (19, 23). Compared with conventional LNAs that typically provide gains between 15 dB and 20 dB (1, 4, 15), the proposed design demonstrates noticeable improvement while maintaining broadband amplification performance.

The gain enhancement is mainly achieved through the stacked common-source topology, which improves amplification capability without significantly increasing power dissipation. Similar gain-enhancement approaches using stacked transistor configurations and optimized matching networks have also been reported in recent GaN RF amplifier studies (2, 3). The simulated noise figure varies from 1.5 dB to 2.2 dB, which is lower than many reported GaN-based X-band LNAs where the NF generally exceeds 2 dB (3, 10, 15). Although GaN devices are widely recognized for high-power and high-temperature operation, achieving low-noise performance remains challenging because of trapping effects, parasitic capacitances, and device nonlinearity (9, 20).

The obtained low-noise performance confirms the effectiveness of inductive source degeneration and optimized impedance matching adopted in this work. Similar observations regarding improved noise performance through impedance optimization were also reported in earlier RF amplifier studies (1, 16). Stability analysis demonstrates that the design exhibits unconditional stability in the X-band because Rollett stability parameter K satisfies $K > 1$ and $|\Delta| < 1$ over the entire operating frequency range. Stability in military RF frontend systems is very important since instability can lead to radar errors and poor communications (6, 19). Impedance stability of the proposed design is further verified using the Smith chart analysis method. Similar stability parameters have also been mentioned in some earlier research work on GaN LNAs (10, 17). An additional advantage of the proposed design is low DC power dissipation. Power consumed by the proposed design is less than 3 W while several existing GaN LNA designs dissipate more power due to biasing and thermal conditions (5), (24).

This is mainly achieved by utilizing current mirror biasing and optimization of the amplifier stage design. Low power dissipation makes it easy to dissipate heat and makes it easy to incorporate into small size defense communication devices and aircraft radars (6, 19). As can be seen from the table below showing the comparative analysis, it can be noted that the proposed design enhances gain, noise figure, impedance match, and also power dissipation. It contrasts other designs whose emphasis was on enhancing only gain or reducing noise (1, 3, 10). As such, the design offers multi-objective optimization which is suitable for military use. Nonetheless, there are a few drawbacks with the current research.

The Simulation-oriented techniques have been used in the development of this device. Also, effects such as parasitic coupling, packaging, process variations, and thermal coupling have not been considered in the current study since these effects cannot be simulated. Finally, important linearity figures such as IP3 and P1dB have not been calculated yet. The next step would be to experimentally validate this design and perform linearity and thermal reliability studies.

5. CONCLUSION

This paper has highlighted the development of a low power consuming and high efficiency Gallium Nitride (GaN) based low noise amplifier (LNA) designed for military use in applications such as communications and radar in the X band range (8–12 GHz). The proposed LNA design seeks to address some of the major problems associated with the traditional GaN LNA designs, especially the conflict among gain, noise figure, and power dissipation through application oriented design approach.

The LNA design incorporates a stacked common source configuration which facilitates high gain and enhanced ability to handle higher voltages. Besides, the design incorporates an efficient impedance matching circuitry ensuring effective power transfer and reduced losses due to reflections. Moreover, the LNA design makes use of the current mirror biased technique facilitating even current distribution in all stages.

The simulation results show that the developed LNA gives a gain value of 18-22 dB, has low noise figure values ranging from 1.5 to 2.2 dB, and has both input and output return losses less than -15 dB within the frequency range of X-band. Moreover, the power consumption level remains less than 3 W, and this is considered a marked improvement compared to many of the existing GaN LNAs. It is evident that the developed LNA provides better performance and power consumption levels compared to other designs, thus making it a feasible candidate for future military applications in the field of RF front-end systems.

From the discussion presented above, it can be seen that the designed GaN LNA offers a reliable, portable, and efficient means of achieving high gains in high frequency applications. Due to its low noise levels and low power consumption, it is highly applicable to modern communication and defense systems where efficiency and reliability are critical factors. Further work will concentrate on developing a hardware prototype for the amplifier.

The future scope of research involves:

a) Implementation of the proposed LNA hardware
b) Development of the LNA concept for wideband and multiband operations
c) Use of the LNA concept with RF front-end module design
d) Study of optimization algorithms to improve performance
e) Simulation of thermal management for better reliability

Abbreviations

LNAs: Low-Noise Amplifiers, GaN: Gallium Nitride, GaSa: Gallium Arsenide, NF: Noise Figure.

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Author contributions

All authors contribute equally to the research, design the study, analyzed data and approved the final manuscript.

Conflict of Interest

The authors declare that they have no conflict of interest.

Data Availability

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

Declaration of Artificial Intelligence (AI) Assistance

The authors declare that no Artificial Intelligence (AI) tools, software, or automated writing assistance were used in the preparation, analysis or writing of this manuscript.

Ethics Approval

This study does not involve human participants, animals, or any biological materials. Therefore, ethical approval was not required for conducting this research work.

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