International Journal of Electrical and Computer Engineering (IJECE)
Vol. 15, No. 4, August 2025, pp. 3833~3842
ISSN: 2088-8708, DOI: 10.11591/ijece.v15i4.pp3833-3842

Efficient high-gain low-noise amplifier topologies using GaAs FET at 3.5 GHz for 5G systems

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Article Info

Article history:

Received Oct 31, 2024
Revised Mar 21, 2025
Accepted May 23, 2025

Keywords:

5G
Common-source topology
GaAs FET
Gain
Low-noise amplifier
Noise figure

ABSTRACT

Achieving a gain greater than 18 dB with a noise figure (NF) below 2 dB at 3.5 GHz remains a formidable challenge for low-noise amplifiers (LNAs) in sub-6 GHz 5G systems. This study explores and evaluates various LNA topologies, including single-stage designs with inductive source degeneration and cascade configurations, to optimize performance. The single-stage topology with inductive source degeneration achieves a gain of 18.141 dB and an NF of 1.448 dB, while the cascade-stage common-source low-noise amplifier with inductive degeneration achieves a gain of 32.714 dB and a noise figure of 1.563 dB. These results underscore the importance of GaAs FET technology in meeting the demanding requirements of 5G systems, specifically in the 3.5 GHz frequency band. The advancements demonstrated in gain, noise figure, and linearity affirm the viability of optimized LNA topologies for high-performance 5G applications, supporting improved signal quality and reliability essential for modern telecommunication infrastructure.

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1. INTRODUCTION

The low noise amplifier (LNA) is a critical component and the initial stage of a radio frequency (RF) receiver, playing a key role in wireless communication systems [1]. Its primary function is to amplify weak signals received by the antenna while minimizing the introduction of additional noise, thereby preserving the overall noise figure (NF) of the system [2]. Due to its importance in the RF front-end, the design of the LNA must emphasize achieving a low noise figure and high gain to ensure optimal receiver performance [3]. LNAs are essential in various applications, including wireless communications, astronomy, radar, satellite communications, and telecommunications systems. Additional design considerations encompass linearity and stability [4].

Historically, LNAs have been optimized for various technologies, including 3G and 4G frequency bands. However, with the advent of 5G starting in 2019, new requirements have emerged, rendering LNAs designed for 4G communications insufficient for 5G applications [5]. The higher data rates, improved performance demands, and expanded frequency ranges of 5G systems necessitate LNAs specifically designed to meet these challenges [6]. Consequently, the focus has shifted to sub-6 GHz frequency bands within the 5G spectrum, particularly the 3.5 GHz band [7], which plays a critical role in enhancing both quality of service and communication system efficiency as part of 5G new radio (NR) technologies [8]. Engineers are developing new circuits and improving existing topologies to ensure that devices can operate effectively in this frequency range [9].

Various LNA topologies have been investigated by researchers for their suitability in 5G applications, each offering distinct performance advantages. For instance, the common-source amplifier topology, as demonstrated in [10] using a gallium arsenide field-effect transistor (GaAs-FET), achieves a notable maximum gain of 15.436 dB and an NF of 1.908 dB for [3.3-3.9] GHz 5G systems. In another example, a cascode topology designed for 5G (3-4 GHz) wireless receivers employs a 400 µm GaAs transistor, achieving an NF of 0.8 dB and a gain of 13.3 dB, as reported in [11]. Additionally, the common-source amplifier with inductive source degeneration topology, utilizing GaAs pseudomorphic high electron mobility transistor (GaAs pHEMT) processes, has been shown to achieve an NF of 1.3-1.4 dB and a gain of 20 to 21 dB for 3.2 to 3.8 GHz systems [12], These topologies offer trade-offs in gain, NF, and linearity. However, the choice of topology depends on the specific system requirements and performance targets.

Achieving a gain greater than 18 dB with an NF below 2 dB at 3.5 GHz is a critical challenge for improving signal quality and ensuring efficient 5G system performance [13]. A comparative analysis of semiconductor technologies such as InP, SiGe, GaAs FET, and Si reveals that GaAs FET technology offers an optimal balance of gain, noise figure, and frequency response, making it a strong candidate for LNA design in this band [14]. Our findings indicate that the single-stage LNA using GaAs FET achieves a gain of 18.141 dB and an NF of 1.448 dB, successfully addressing this challenge. Cascading this topology increases the gain to 32.714 dB, with a modest rise in NF to 1.563 dB. These advancements in LNA design enhance system efficiency, expand coverage, and improve capacity, meeting the demanding requirements of modern 5G networks and ensuring reliable, high-performance telecommunications infrastructure.

2. DESIGN OF LOW NOISE AMPLIFIER

In low noise amplifier (LNA) design, several key steps need to be addressed, followed by the evaluation of critical performance metrics [15]. The first step is selecting an appropriate transistor [16], as transistors are optimized for specific frequency ranges based on their structure and manufacturing process. This selection is critical for meeting the design's performance criteria [17]. A suitable direct current (DC) biasing network is then designed to set the operating point of the transistor, ensuring consistent performance [18]. Typically, an active bias network is preferred to maintain stability under varying operating conditions [19]. In this design, a specific biasing network is implemented to achieve the desired operating point [20]. Impedance matching is another crucial aspect of LNA design, as improper matching can severely degrade system performance [21]. The primary objective is to match the load impedance with the source impedance to optimize signal transfer [22]. Various methods, such as LC, stub, T, and Pi networks [23], are commonly employed for this purpose, with Smith charts often used to facilitate practical implementation [24].

Key performance metrics must be carefully considered to achieve optimal functionality. The first metric, gain, refers to the ratio of the output signal to the input signal [25]. For an LNA, this means the output power must exceed the input power, resulting in a positive gain measured in dB [26]. Typically, a single-stage LNA achieves a gain of over 10 dB and an NF below 5 dB [27], with additional stages cascaded to further enhance the overall gain when necessary. Another critical parameter is the noise figure, which quantifies the noise introduced by the system. A lower NF is essential for improving overall performance and increasing system sensitivity, making NF a primary consideration in transistor selection [28]. Beyond gain and NF, two additional factors play a crucial role in ensuring reliable LNA operation: stability and linearity. Stability is essential, as an unstable amplifier may oscillate, leading to performance degradation or complete circuit failure. It is evaluated using S-parameters, with the stability factor K serving as a key indicator [29]. An amplifier is absolutely stable when the following conditions are met [30]:

$$K = \frac{1-|S_{11}|^2-|S_{22}|^2+|\Delta|^2}{2|S_{12}S_{21}|} > 1 \quad (1)$$

$$|\Delta| = |S_{11}S_{22} - S_{12}S_{21}| < 1 \quad (2)$$

Here, S_{11} and S_{22} are reflection coefficients, and S_{21} and S_{12} are transmission coefficients, and Δ is the determinant of the 2-port scattering matrix [31]. Linearity, on the other hand, ensures that the amplifier's output power changes proportionally with the input power, crucial for handling large signals without significant distortion [32]. This characteristic is typically assessed by the 1 dB compression point, which indicates the input level at which the gain drops by 1 dB from its ideal linear response. Maintaining good linearity prevents signal degradation, especially in high-performance communication systems [33].

3. METHOD

In this work, a low noise amplifier was developed using the s8834 GaAs FET transistor, a microwave semiconductor characterized for the 3 to 10 GHz frequency band. The design employs an common-source with inductive degeneration topology optimized for the 3.3 to 3.7 GHz frequency range, crucial for 5G wireless applications. Simulations were performed using advanced design system (ADS) 2009 to optimize key performance metrics. The circuit includes a designed DC biasing network to set the optimal operating point for the transistors, ensuring consistent performance with a 5V DC supply. Impedance matching is achieved through a combination of LC networks, which align the load and source impedances for optimal signal transfer and minimal reflection losses.

The key components of the design include coupling capacitors (C_1, C_2) to isolate DC while preserving RF signal integrity and biasing resistors (R_2, R_3) to ensure proper transistor biasing. Inductor L_1 serves as a bias inductor, providing a high impedance path for RF signals. On the output side, resistor R_4 establishes the transistor's bias point, while inductor L_2 enhances gain and output characteristics. The input and output impedance matching networks (L_4, C_3 and L_5, C_4, respectively) are designed to maximize power transfer and amplifier efficiency. An inductive source degeneration topology, with L_3 at the source of the primary transistor (M_1) is employed to stabilize gain, improve linearity, and reduce the noise figure.

However, the single stage common-source LNA with inductive degeneration in Figure 1 achieved a low noise figure but lacked sufficient gain to meet stringent performance requirements. To address this, a cascade stage common-source LNA with inductive degeneration in Figure 2 was developed, utilizing two GaAs FETs (M_1 and M_3) and biasing transistors (M_2 and M_4). This design enhances gain while maintaining a low noise figure, resolving the limitations of the single-stage design for 5G applications.

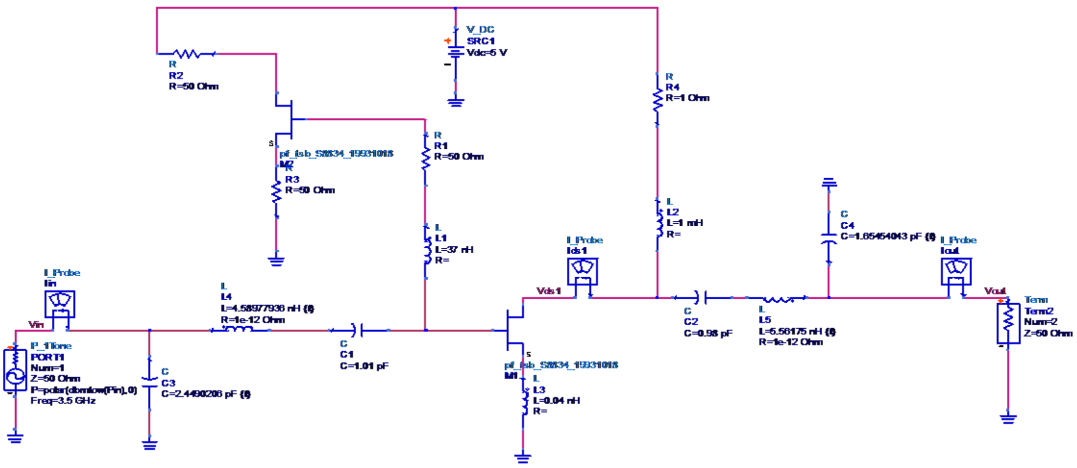

Figure 1. Single stage common-source LNA with inductive degeneration

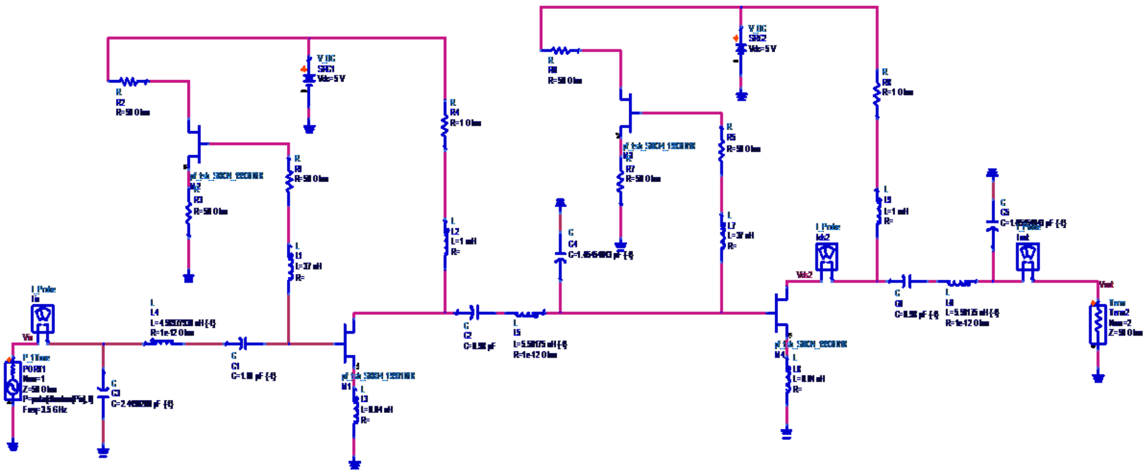

Figure 2. Cascade stage common-source LNA with inductive degeneration

4. RESULT AND DISCUSSION

The performance of each LNA topology was evaluated based on gain, noise figure (NF), stability, and linearity, with configurations optimized for maximum gain and minimum NF to ensure efficient operation within the target frequency band. Impedance matching was crucial to optimize power transfer and minimize signal reflections. Simulation results and a comparative analysis of the single-stage and cascade-stage configurations are summarized in Table 1, where key parameters such as gain, NF, K and Δ, and impedance matching (S_{11}, S_{22}) are compared with the required performance criteria. This analysis demonstrates the reliability of the design methodology and the improvements achieved through optimization.

Table 1. Performance metrics for each LNA topology

Parameters	Requirements	Single stage common-source LNA with inductive degeneration	Cascade stage common-source with inductive degeneration
Gain (dB)	>18	18.141	32.714
NF (dB)	< 2	1.448	1.563
K	>1	1.002	1.472
Δ	<1	0.690	0.392
S_{11} (dB)	< -10	-12.223	-34.006
S_{22} (dB)	< -10	-22.530	-57.787

4.1. Single stage common-source low noise amplifier with inductive degeneration

The single stage common-source LNA with inductive degeneration initially faced challenges in achieving adequate gain. Optimization addressed these limitations as shown in Figure 3, resulting in a stability factor K of 1.002 and Δ of 0.690 at 3.5 GHz as shown in Figure 3(a). The design achieved a gain of 18.141 dB and an NF of 1.448 dB GHz as shown in Figure 3(b), making it the most noise-efficient among the single-stage configurations. Additionally, impedance matching was effective, with S_{11} of -12.223 dB and S_{22} of -22.530 dB GHz as shown in Figure 3(c). The power-added efficiency (PAE) reached 27.506% GHz as shown in Figure 3(d) indicating high efficiency. The output voltage V_{out} was 1.448 V, the input voltage V_{in} was 0.386 V as shown in Figure 3(e), and the output power was 13.076 dBm as shown in Figure 3(f), reflecting moderate amplification of the input signal. Despite these strengths, the gain was insufficient to meet the stringent requirements for 5G applications.

4.2. Cascade stage common-source low noise amplifier with inductive degeneration

To overcome the gain limitations of the single-stage design, the cascade topology was adopted by adding an additional amplification stage with inductive degeneration. This design demonstrated, as shown in Figure 4 a stability factor K of 1.472 and a Δ of 0.392 at 3.5 GHz as shown in Figure 4(a). The optimized configuration achieved the highest gain of 32.714 dB and an NF of 1.563 dB as shown in Figure 4(b). While the NF was slightly higher than the single-stage design, it presented a favorable trade-off between noise and gain. Impedance matching was excellent, with S_{11} of -34.006 dB and S_{22} of -57.787 dB as shown in Figure 4(c). The output voltage V_{out} was 1.720 V and the input voltage V_{in} was 0.528 V as shown in Figure 4(e), resulting in an output power of 14.525 dBm as shown in Figure 4(f). The PAE was measured at 21.226% as shown in Figure 4(d), slightly lower than the single-stage design due to the additional amplification stage. This reduction in PAE reflects the inherent trade-off between higher gain and efficiency; however, the resulting PAE remains sufficient for high-performance 5G applications.

Table 2 presents a detailed comparison of the proposed LNA with existing topologies, demonstrating its superior performance. The cascade-stage LNA with inductive degeneration achieves the highest gain (32.714 dB), significantly surpassing the gain of the common-source topology using GaN HEMT transistors (16.225 dB) in [34]. While its noise figure (1.563 dB) is slightly higher than those reported in other references, the proposed design exhibits excellent impedance matching, with S_{11} = -34.006 dB and S_{22} = -57.787 dB, outperforming all references. This analysis highlights the trade-offs between gain and noise figure, positioning the proposed LNA as a well-balanced, high-performance solution for 5G sub-6 GHz applications.

This analysis confirms the importance of selecting the right LNA topology for specific 5G applications. While the single-stage LNA with inductive degeneration excels in noise performance and efficiency, the cascade-stage topology, by offering higher gain, is more suited for applications where gain is the primary requirement. Future work should focus on further optimizing the cascade-stage LNA for a better balance between noise figure and efficiency to meet the evolving needs of 5G systems.

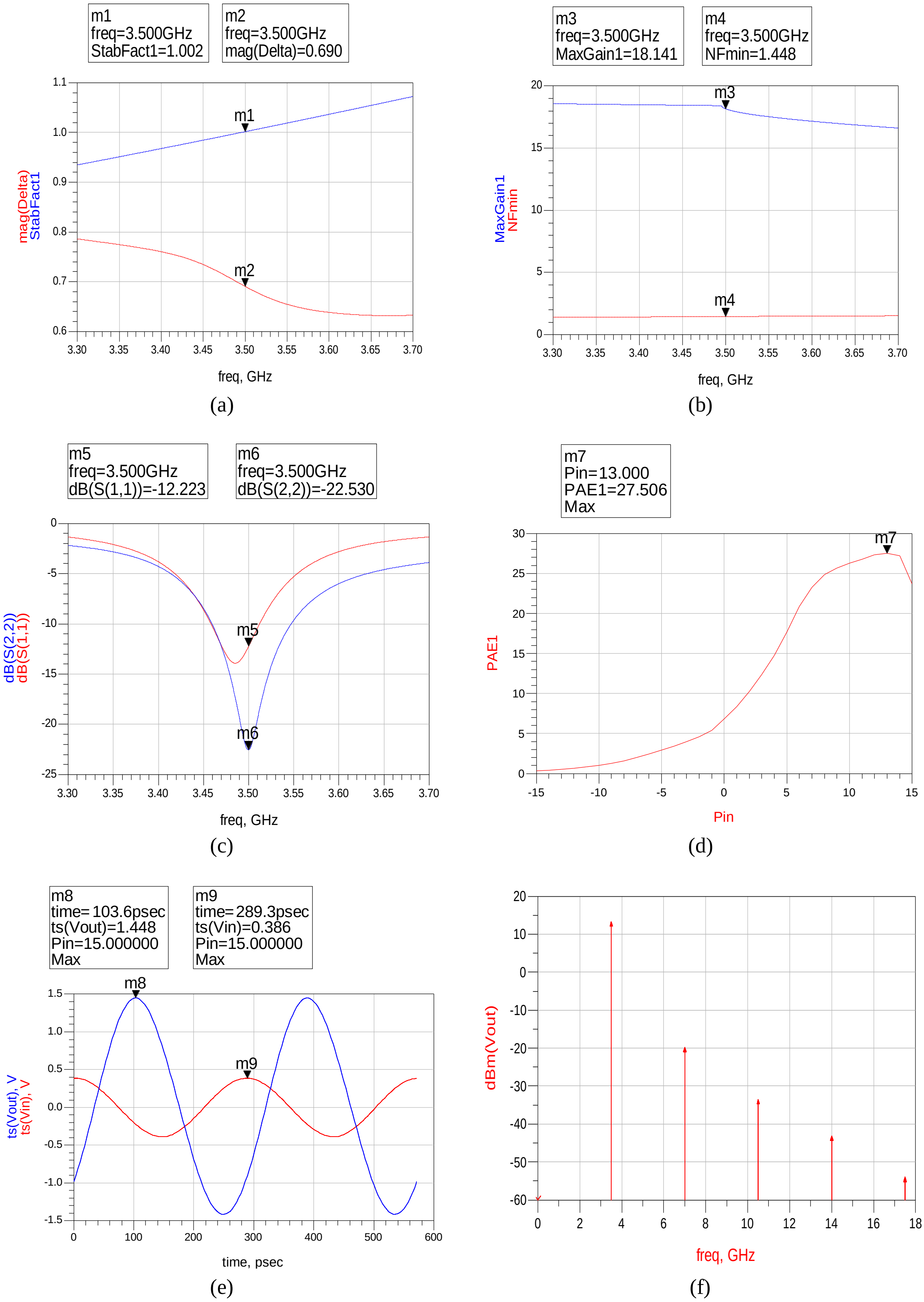

Figure 3. Performance metrics of single stage common-source LNA with inductive degeneration topology: (a) stability factor K and delta Δ, (b) noise figure NF and gain, (c) S-parameters, (d) power added efficiency (PAE) versus output power, (e) output and input signals and (f) harmonic spectrum

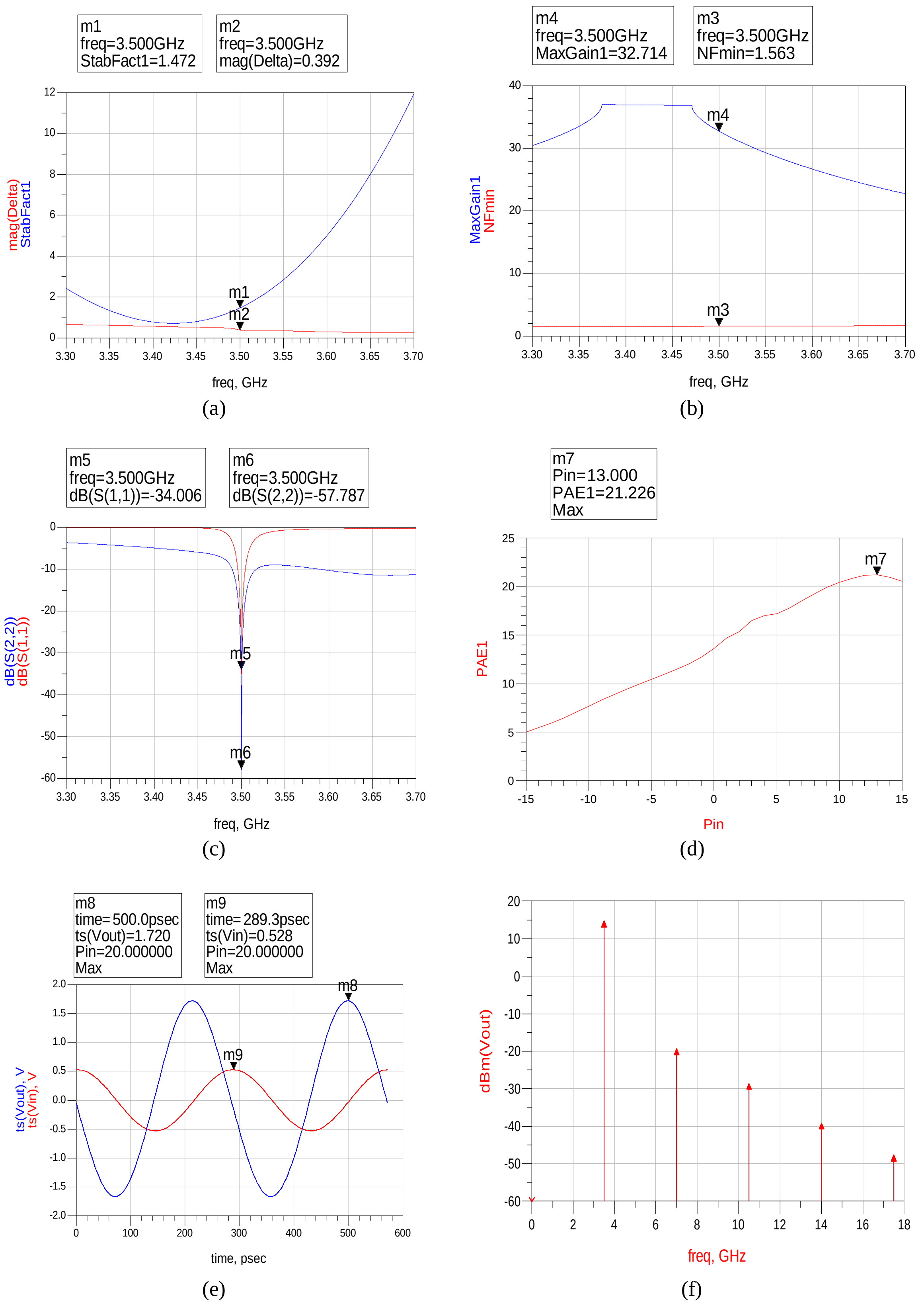

Figure 4. Performance metrics of cascade stage common-source LNA with inductive degeneration topology: (a) stability factor K and delta Δ, (b) noise figure and gain, (c) S-parameters, (d) power added efficiency (PAE) versus output power, (e) output and input signals, and (f) harmonic spectrum

Table 2. Performance overview and comparison of the present study with existing LNAs

Reference	[34]	[35]	[36]	[37]	This work
Technology	GaN HEMT	CMOS 110 nm SOI	GaAs pHEMT	GaAs pHEMT	GaAs FET
Topology	Common source	Cascode inductive source degeneration	Cascade CS-CS	Two-stage	Cascade stage common-source with inductive degeneration
Frequency [GHz]	3.5	2.4–3.5	4-8	4.2–5.2	3.5
Application	Sub-6GHz	LTE/5G NR	Sub-6GHz	Sub-6GHz	Sub-6GHz
Transistor model	CGH35	-	0.25 µm	0.5µm	s8834
Gain [dB]	16.225	20	21.5	27.6	**32.714**
Noise Figure [dB]	1.232	1.5	1.43	0.66	1.563
S11 [dB]	-23.785	-	< -14	-	**-34.006**
S22 [dB]	-23.516	-	< -11	-	**-57.787**

5. CONCLUSION

This study provides a detailed evaluation of various LNA topologies designed for 5G systems operating at 3.5 GHz, with a focus on achieving high gain and optimal noise figure using GaAs FET technology. The single-stage common-source LNA with inductive degeneration demonstrated superior noise performance, achieving an NF of 1.448 dB and a gain of 18.141 dB, it well-suited for applications requiring low noise. In contrast, the cascade-stage configuration offered a significantly higher gain of 32.714 dB, proving effective for scenarios demanding greater signal amplification. These findings highlight the advantages of GaAs FET technology, particularly in sub-6 GHz 5G systems where both low noise and high gain are essential. Future research should aim to further enhance these designs by optimizing performance for different 5G application requirements.

FUNDING INFORMATION

The authors gratefully acknowledge the financial assistance provided by the Scientific Publication Support Center at Ibn Tofail University. This support helped cover the publication expenses and facilitated the broader dissemination of the research outcomes

AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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C : **C**onceptualization
M : **M**ethodology
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I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

The authors declare that there are no conflicts of interest

DATA AVAILABILITY

The dataset underlying the results of this study is publicly presented in Table 1. It includes the parameter values used during simulations performed with ADS 2009. Researchers may refer to the dataset in Table 1 for replication purposes or to support further investigations.

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