Design and Performance Analysis of GFET Power Amplifier at D-band

PROJECT REPORT

Submitted in the fulfilment of the requirements for

the award of the degree of

Bachelor of Technology
in
Electronics and Communication Engineering

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(ACCREDITED BY **NAAC** WITH **"A+"** GRADE)

DEPARTMENT OF ELECTRONICS AND COMMUNICATION ENGINEERING
(ACCREDITED BY **NBA**)

VIGNAN'S FOUNDATION FOR SCIENCE, TECHNOLOGY AND RESEARCH
(Deemed to be University)

Vadlamudi, Guntur, Andhra Pradesh, India -522213

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CERTIFICATE

This is to certify that project report entitled **"Design and Performance Analysis of GFET Power Amplifier at D-band"** that is being submitted by Shaik Arshiya [201FA05075], Chikkam Sai ManiKanta [201FA05078], Sadhu Jaya Ajay Kumar [201FA05086] and Pittu Pravalika [211LA05013] in fulfilment for the award of B. Tech degree in Electronics and Communication Engineering, Vignan's Foundation for Science Technology and Research University, is a record of bonafide work carried out by them under the guidance of Dr. G. Pradeep of ECE Department.

Signature of the guide
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23/5/24.
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Professor & HoD ECE

DECLARATION

We hereby declare that the project report entitled **"Design and Performance Analysis of GFET Power Amplifier at D-band"** is being submitted to Vignan's Foundation for Science, Technology and Research (Deemed to be University) in fulfilment for the award of B. Tech degree in Electronics and Communication Engineering. The work was originally designed and executed by us under the guidance of Dr. G. Pradeep at the Department of Electronics and Communication Engineering, Vignan's Foundation for Science Technology and Research (Deemed to be University) and was not a duplication of work done by someone else. We hold the responsibility of the originality of the work incorporated into this project report.

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ABSTRACT

This project focuses on designing and analyzing the performance of a GFET-based power amplifier tailored for D-band frequencies (110-170 GHz), aiming to address the increasing demand for high-speed data transmission and ultra-low latency in wireless communication, radar, and imaging technologies. Traditional amplifier technologies encounter significant hurdles in achieving high gain, broadband operation, and efficiency at these frequencies. Graphene Field-Effect Transistors (GFETs) emerge as promising candidates due to their superior carrier transport properties and reduced parasitic capacitance. The design specifications include a frequency range of 110-170 GHz with a 20 GHz bandwidth, an output power of 18dBm, a gain exceeding 10 dB, a drain efficiency 75%, a return loss below -15 dB, and a Power Added Efficiency (PAE) of over 62%.

The successful development of such amplifiers holds the potential to greatly enhance next-generation communication systems, radar applications, and high-resolution imaging technologies, enabling faster data rates, precise object detection, and detailed imaging. This project aims to contribute to the advancement of D-band frequency amplification technology, facilitating the adoption of high-frequency wireless communication systems and fostering innovations in telecommunications and related fields, providing a comprehensive guide for engineers and researchers in GFET-based amplifier design by integrating theoretical insights with practical strategies.

Keywords: Power Amplifier; High Efficiency; GFET; High Gain; D-Band.

Major Design Constants and Design Standards Table

Student Group	Sk. ARSHIYA (201FA05075)	CH.SAI MANIKANTA (201FA05078)	S. JAYA AJAY KUMAR (201FA05086)	P. PRAVALIKA (211LA05013)

Project Title	DESIGN AND PERFORMANCE ANALYSIS OF GFET POWER AMPLIFIER AT D-BAND
Program Concentration Area	RF Front-end Design at Sub-THz regime
Constraints – Examples	
Economic	Fixed Budget
Environmental	Friendly
Sustainability	The designed Power Amplifier has a high drain efficiency which sustain for long working hours
Manufacturability	Yes
Ethical	Followed the standard professional ethics
Health and Safety	FCC guide lines are followed
Social	Applicable for Telecommunications
Political	None
Other	The primary component in the entire transmitter design is PA, which is responsible for the performance of RF transmitter as it contributes to the overall output power efficiency, bandwidth, linearity and gain
Standards	
1. IEEE Std 802.3af-2011 2. IEEE 1597.1-2008	IEEE Standard for D-Band Frequency (110-170GHz) IEEE Standard for ADS Software Tool
Previous Course Required for the Major Design Experience	1. Analog Electronics 2. Electromagnetic waves and Transmission Lines

Supervisor **Project Co-Ordinator** **Head of the department ECE** 23/5/24.

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Acronyms

ACC	Adaptive Cruise Control
ADAS	Advance Driver Assistant Systems
ADS	Advance Design System
CMOS	Complementary Metal Oxide Semiconductor
dB/dBm	Decibel/Decibel-milli
DC	Direct Current
EGFET	Electrolyte-Gated Field Effect Transistor
EMS	Electromagnetic Simulator
FCC	Federal Communications Commission
GFET	Graphene Field Effect Transistor
Gmax	Maximum Achievable Gain
IC	Integrated Circuits
IEEE	Institute of Electrical and Electronics Engineers
LC	Inductor & Capacitor
MLIN	Microstrip Line
MLOC	Main Line Output Coupler
mm	Millimeter
MMIC	Monolithic Microwave Integrated Circuit
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
MSUB	Microstrip Substrate
PA	Power Amplifier
PAE	Power Added Efficiency
PWM	Pulse Width Modulation
RF	Radio Frequency
RFIC	Radio-Frequency Integrated Circuit

THz	Tera Hertz
ZVS	Zero-Voltage Switching

CHAPTER I

1.1 INTRODUCTION

High-speed applications such as radar, imaging, and emerging 6G communication systems are increasingly leveraging advanced semiconductor technologies to achieve superior performance. Among these technologies, Graphene Field-Effect Transistors (GFETs) have gained significant attention, particularly for their use in power amplifiers operating at D-band frequencies (110-170 GHz). Modern radar systems, used in various sectors including automotive, aviation, and military, require high-frequency operation to achieve better resolution and accuracy. The D-band frequency that follows IEEE Std 802.3af-2011. D-band frequencies are particularly advantageous for short-range, high-resolution radar applications. GFETs offer high electron mobility and saturation velocity, which translates into faster signal processing and enhanced sensitivity in radar systems. This capability allows for the detection of smaller objects and more precise imaging of targets, crucial for advanced driver assistance systems (ADAS) and autonomous vehicle technologies.

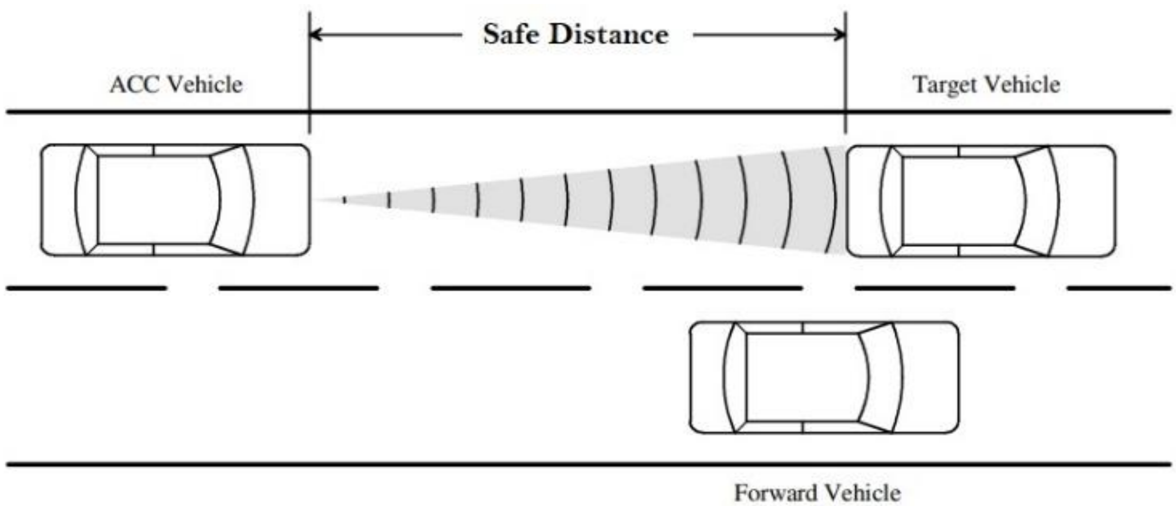

Fig 1.1 Adaptive Cruise Control (radar application)

Imaging technologies benefit significantly from operating at D-band frequencies, particularly in medical diagnostics, security scanning, and industrial inspection. The high frequencies enable detailed imaging due to shorter wavelengths, which provide higher resolution. The Power Amplifier that follows 802.11 ac. GFET-based power amplifiers, with their high-frequency operation and excellent thermal conductivity, support the generation and amplification of signals needed for high-resolution imaging. This results in clearer images with finer detail, essential for detecting anomalies or conducting non-invasive examinations. The development of 6G communication networks aims to provide ultra-fast data transmission, low latency, and enhanced connectivity. Operating at D-band frequencies is a key enabler for achieving the high data rates envisioned for 6G. GFETs, known for their high-speed electronic properties and ability to handle high-frequency signals, are ideal for power amplifiers in these networks. They support the massive bandwidth requirements and facilitate the efficient amplification of signals, which is crucial for maintaining signal integrity over long distances and through various media.

Hence, GFET-based power amplifiers represent a significant advancement in the field of high-speed applications operating at D-band frequencies. Their unique properties make them well-suited to meet the demanding requirements of modern radar systems, high-resolution imaging technologies, and the next generation of communication networks. As research and development in graphene technology continue, we can expect even greater enhancements in performance and new capabilities in these high-speed applications.

1.2 MOTIVATION

In today's era of wireless communication, the demand for high-speed data transmission and ultra-low latency has surged exponentially. To meet this demand, there is a critical need for power amplifiers that can efficiently amplify signals at extremely high frequencies, such as the D-band (110-170 GHz). This frequency range holds immense potential for applications in next-generation wireless communication systems, high-speed data transfer, and radar systems. However, the design and implementation of power amplifiers operating at D-band frequencies pose significant challenges. Traditional amplifier technologies struggle to provide the required performance metrics such as high gain, broadband operation, and high efficiency in this frequency range.

This project aims to address this need by focusing on the design and performance analysis of a GFET (Graphene Field-Effect Transistor) power amplifier specifically tailored for D-band frequencies. GFETs have emerged as promising candidates for high-frequency amplification due to their unique properties such as high carrier mobility, high carrier saturation velocity, and excellent thermal conductivity. The primary motivation behind this project is to develop a GFET-based power amplifier that achieves high efficiency and gain across the D-band frequency spectrum. By leveraging the inherent advantages of GFET technology, such as superior carrier transport properties and reduced parasitic capacitance, we aim to design a power amplifier capable of delivering unprecedented performance in terms of power efficiency, gain, and bandwidth.

The successful realization of a GFET-based power amplifier at D-band frequencies will have profound implications across various industries. It can enable the development of next-generation communication systems capable of supporting ultra-high data rates, enhance the performance of radar systems for defense and surveillance applications, and pave the way for advancements in wireless connectivity for emerging technologies such as 6G and beyond. Through comprehensive performance analysis and optimization, this project seeks to contribute to the advancement of D-band frequency amplification technology, thereby accelerating the adoption of high-frequency wireless communication systems and unlocking new possibilities for innovation in the field of telecommunications.

In conclusion, the design and performance analysis of a GFET power amplifier at D-band frequencies represent a significant step towards addressing the growing demand for high-speed, high-frequency communication systems. By pushing the boundaries of amplifier technology, this project aims to facilitate the development of robust, efficient, and high-performance amplifiers capable of meeting the evolving needs of modern wireless communication.

1.3 OBJECTIVE

To outline a design approach for a high-efficiency, high-gain broadband Power Amplifier that operates in the D-band frequency range using GFET technology. It will utilize insights gathered from a prior investigation into GFET device behavior at Sub-THz frequencies to identify crucial design parameters and considerations for optimal performance in the D-band. By combining theoretical principles with practical strategies, the report intends to offer guidance for engineers and researchers dealing with the complexities of GFET-based amplifier design. Ultimately, this effort seeks to advance D-band frequency amplification technology for use in future wireless communication systems.

CHAPTER II

2.1 THEORY

This chapter describes about the theory of Power Amplifier, D-Band, GFET.

2.2 Power Amplifier

A power amplifier is a type of electronic amplifier designed to increase the magnitude of the input signal power to drive loads such as speakers, RF transmitters, or other output devices. Key Characteristics of Power Amplifiers

Efficiency: A measure of how well the amplifier converts input power into output power. Efficiency varies significantly among different amplifier classes.

Linearity: The ability of the amplifier to faithfully reproduce the input signal without distortion. High linearity is crucial for audio and some RF applications.

Gain: The ratio of output power to input power, determining how much the amplifier increases the signal strength.

Thermal Management: Managing heat generated by the power transistors to prevent thermal runaway and ensure reliable operation. Heat sinks, cooling fans, and thermal shutdown circuits are commonly used. The theory behind power amplifiers encompasses several key principles and components.

2.2.1 Classification by Operation Mode

Power amplifiers are classified into different classes based on their operation mode, which significantly impacts their efficiency, linearity, and application. The most common classes include:

- **Class A:**

  Operation: The active device (transistor or tube) conducts for the entire cycle (360 degrees) of the input signal.

  Characteristics: High linearity and low distortion, but poor efficiency (maximum theoretical efficiency is 25-30%).

  Application: High-fidelity audio amplification.

- **Class B:**

  Operation: The active device conducts for half of the input signal cycle (180 degrees).

  Characteristics: Higher efficiency than Class A (up to 78.5% theoretical efficiency), but can suffer from crossover distortion.

  Application: Audio amplification where efficiency is more critical, often used in push-pull configurations.

- **Class AB:**

  Operation: The active device conducts for more than half but less than the entire cycle (180-360 degrees).

  Characteristics: Compromise between Class A and Class B, offering better efficiency than Class A and reduced distortion compared to Class B.

  Application: Widely used in audio amplification.

- **Class C:**

  Operation: The active device conducts for less than half of the input signal cycle (less than 180 degrees).

  Characteristics: Very high efficiency (up to 90%), but high distortion, making it suitable for RF amplification where signals can be filtered.

  Application: RF transmitters.

- **Class D:**

  Operation: Uses pulse-width modulation (PWM) or other digital techniques to switch the output device on and off rapidly.

  Characteristics: Very high efficiency (up to 90-100%), suitable for audio applications due to advancements in filtering techniques.

  Application: Audio amplification, especially in portable and battery-powered devices.

- **Class E:**

  Operation: Utilizes a switching mode where the active device (typically a MOSFET) is turned on and off in a manner that minimizes the overlap of voltage and current waveforms. This is achieved with the help of a resonant LC circuit that ensures zero-voltage switching (ZVS), reducing power dissipation.

  Characteristics: Very high efficiency (often greater than 70% and up to 90%), with relatively simple circuit design. However, they exhibit high harmonic content and nonlinear operation, making them suitable for specific applications. Performance is highly dependent on precise component values in the resonant circuit.

Application: Primarily used in RF transmitters, wireless power transfer systems, industrial RF applications (such as RF heating and plasma generation), and certain medical devices (like RF ablation equipment).

- **Class F:**

  Operation: Employs harmonic tuning using multiple resonant circuits to shape the voltage and current waveforms at the output, achieving high efficiency by reducing the overlap of voltage and current. This typically involves tuning the load network to enhance certain harmonics and suppress others, optimizing the switching transitions.

  Characteristics: High efficiency (often greater than 70% and potentially up to 90%), with improved power output and reduced heat dissipation. The harmonic tuning allows for better performance at high frequencies, but the design is more complex and requires precise control of harmonic content.

  Application: Mainly used in RF and microwave amplification for applications like communication transmitters, radar systems, and other high-frequency, high-power systems where efficiency and performance are critical.

2.3 D – BAND:

The D-band refers to a specific range of frequencies within the electromagnetic spectrum, typically used for high-frequency communications and advanced radar applications. The D-band generally covers frequencies from 110 GHz to 170 GHz.

- **Characteristics:**

  High Frequency: The D-band operates in the millimeter-wave (mm Wave) range, which means it has very short wavelengths (approximately 1.8 mm to 2.7 mm).

High Bandwidth: The high frequencies allow for large bandwidths, which can support very high data rates.

Propagation Characteristics: D-band signals tend to have high atmospheric attenuation, meaning they are absorbed more by the atmosphere compared to lower frequency bands. This limits their range but can be mitigated with high-gain antennas and line-of-sight transmission.

- **Applications:**

High-Speed Wireless Communications: The D-band is increasingly being explored for ultra-high-speed wireless communication systems, including 5G and beyond (6G). The large bandwidth available in this band can support extremely high data rates, suitable for applications like wireless backhaul and front haul in cellular networks.

Radar Systems: The D-band is used in advanced radar systems for applications such as automotive radar, security imaging, and military radar. The high frequency allows for better resolution and more precise detection of objects.

Scientific Research: Due to its unique properties, the D-band is also used in scientific research, including atmospheric studies and spectroscopy.

Satellite Communications: Potential use in satellite communications for high-capacity links, although the atmospheric attenuation must be carefully managed.

2.4 GRAPHENE FIELD-EFFECT TRANSISTOR (GFET)

Graphene Field-Effect Transistors (GFET) are a type of field-effect transistor that use graphene as the channel material. Graphene, a single layer of carbon atoms arranged in a two-dimensional honeycomb lattice, has unique electronic properties that make GFETs promising for various applications in electronics and sensing. Here’s an overview of GFETs:

2.4.1 Structure and Operation

Structure: A typical GFET consists of a graphene channel placed between two contacts (source and drain), with a gate electrode that controls the current flow through the channel. The gate can be located above or below the graphene layer, and it is insulated from the graphene by a dielectric layer.

Operation: Similar to traditional FETs, GFETs operate by applying a voltage to the gate electrode, which modulates the carrier concentration in the graphene channel. This changes the conductivity of the graphene, controlling the current flow between the source and drain terminals.

2.4.2 Properties of Graphene

High Carrier Mobility: Graphene exhibits very high electron and hole mobility, allowing for faster electronic devices compared to silicon-based transistors.

Ambipolar Conductivity: Graphene can conduct both electrons and holes, enabling unique device functionalities.

High Thermal Conductivity: Graphene’s excellent thermal conductivity helps in efficient heat dissipation, which is beneficial for high-power applications.

Mechanical Strength and Flexibility: Graphene’s strength and flexibility open up possibilities for flexible and wearable electronics.

Optical Transparency: Graphene is remarkably transparent, absorbing only about 2.3% of visible light per layer, making it suitable for transparent conductive films in displays and solar cells.

Tunability: The electronic properties of graphene can be tuned by applying an external electric field, chemical doping, or modifying its structure, allowing control over its carrier concentration and type (electrons or holes).

Chemical Stability: Graphene is chemically stable under a wide range of environmental conditions and resistant to attack by most chemicals due to the strong carbon-carbon bonds and its inert surface.

2.4.3 Characteristics of GFETs

High-Speed Operation: Due to graphene's high carrier mobility, GFETs can operate at very high frequencies, making them suitable for high-speed and RF applications.

Low Noise: GFETs exhibit low electrical noise, which is advantageous for sensitive detection and communication systems.

Scalability: Graphene's atomic thickness allows for the fabrication of very small transistors, contributing to the continued scaling of electronic devices.

2.4.4 Applications

High-Frequency Electronics: GFETs are promising for RF and microwave applications, including communication devices and signal processing.

Sensors: GFETs are used in chemical and biological sensors due to their high sensitivity and the ability to detect single molecules or low concentrations of analytes.

Flexible Electronics: The mechanical properties of graphene make GFETs suitable for flexible and wearable electronic devices.

Optoelectronics: GFETs can be integrated into optoelectronic devices, benefiting from graphene's excellent optical and electronic properties.

Digital and Analog Circuits: GFETs have potential applications in both digital circuits (logic gates, processors) and analog circuits (amplifiers, mixers).

2.4.5 Applications of Power Amplifiers

Audio Amplification: Driving speakers in home audio systems, public address systems, and musical instrument amplifiers.

RF and Microwave Amplification: Used in radio transmitters, television transmitters, cellular base stations, and radar systems.

Industrial Applications: Driving motors, actuators, and other high-power devices in industrial settings.

Wireless Communication: Amplifying signals in communication systems to ensure they can be transmitted over long distances.

CHAPTER III

3.1 LITERATURE REVIEW

3.1.1 Literature review of THz circuits

1. The research paper titled **"Terahertz integrated electronic and hybrid electronic–photonic systems"** by Kaushik Sengupta et al. (2018) in Nature electronics is focused on Development of terahertz (THz) integrated electronic and hybrid electronic-photonic systems for applications in communication, sensing, and imaging. The current state-of-the-art in THz devices, circuits, and systems includes advancements in electronics, photonics, and hybrid technologies.

This involves creating advanced THz systems that integrate electronic and photonic components. These systems are used for various purposes such as improving communication technologies, enhancing sensing capabilities, and advancing imaging techniques. The latest developments cover pure electronic approaches, purely photonic approaches, and combinations of both to optimize performance and functionality in THz applications.

Research gap:

The appropriate technology to support the diverse range of wireless technologies and the convergence of electronics and photonics is still an open area of research. This means that researchers are still investigating the best technology to integrate different wireless systems and combine electronic and photonic components effectively. It is a field that has not yet reached a definitive solution, and ongoing studies are exploring various possibilities to achieve this integration.

2. The research paper titled **"Terahertz electronics: Application of wave propagation and nonlinear processes"** by H. Aghasi et al. (2020) in Applied Physics Reviews describes about Development of integrated circuits (ICs) where electromagnetic waves and electronic components interact. Techniques and methodologies have been developed for efficient millimetre-wave and terahertz signal generation using these integrated electronic components.

This involves creating ICs that facilitate the interaction between electromagnetic waves and electronic parts. Researchers have developed various techniques and methods to generate millimetre-wave and terahertz signals efficiently within these integrated electronic systems.

Research gap:

The efficient combination of integrated electronic circuits and photonic/optical transceivers has shown promising changes. This means that successfully integrating electronic circuits with photonic or optical transceivers has led to significant and positive advancements. Researchers have observed notable improvements and potential benefits from this combination, indicating progress in this area of technology.

3.1.2 Literature review of Device Technology

1. The research paper titled **“A Large-Signal Graphene FET Model”** by Omid Habibpour et al. (2012) in IEEE Transactions on Electron Devices focused on A semi-empirical graphene field-effect transistor (G-FET) model for the analysis and design of G-FET-based circuits. Current-voltage characteristics for a G-FET over a wide range of operating conditions. Designing and analyzing a G-FET-based sub-harmonic resistive mixer. This involves using a semi-empirical model to analyze and design circuits that use G-FETs. It includes studying the current voltage behavior of G-FETs under various operating conditions and focusing on the design and analysis of a sub-harmonic resistive mixer based on G-FET technology.

Research gap:

GFET modeling and characterization at terahertz frequencies. Implementation of GFET device technology for designing front-end amplifiers. This involves creating models and characterizing graphene field-effect transistors (GFETs) at terahertz frequencies. It also includes using GFET technology to design front-end amplifiers.

2. The research paper titled **“A Current–Voltage Model for Graphene Electrolyte-Gated Field-Effect Transistors”** by Charles Mackin et al. (2014) in IEEE Transactions on Electron Devices describes Graphene electrolyte-gated field-effect transistors (EGFETs) that incorporate the effects of the graphene-electrolyte interface and the quantum capacitance of graphene. Device parameters such as mobility, minimum carrier concentration, interface capacitance, contact resistance, and effective charged impurity concentration.

This involves EGFETs that take into account the interaction between graphene and the electrolyte, as well as graphene's quantum capacitance. It includes parameters like mobility, minimum carrier concentration, interface capacitance, contact resistance, and the concentration of effective charged impurities.

Research gap:

Examine graphene material for reconfigurable terahertz (THz) optoelectronics. Explore its capability to electrically tune optical properties across a wide range of THz frequencies. This involves studying graphene's potential for use in reconfigurable THz optoelectronic devices. Researchers are investigating how graphene's optical properties can be adjusted electrically over a broad spectrum of THz frequencies.

3.1.3 Literature Review of D-band Power Amplifier

1.The research paper titled **"A D-Band Power Amplifier in 65-nm CMOS by Adopting Simultaneous Output Power-and Gain-Matched Gmax-Core"** by Dae-Woong Park et al. (2021) in IEEE Transactions on Electron Devices is focused on a simultaneous output power- and gain-matching technique is proposed for designing a sub-THz power amplifier (PA) based on a core with maximum achievable gain (Gmax). This technique aims to optimize both output power and gain in the PA design.

THz systems operating within the D-band frequency range (110-170 GHz) are advancing quickly for various wireless applications including radar, high-data-rate next-generation (6G) communication systems, and imaging. This frequency range holds promise for enabling new technologies and enhancing wireless capabilities in these fields.

Research gap:

In CMOS power amplifiers, achieving a Power Added Efficiency (PAE) exceeding 20% is considered significant, particularly at higher frequency bands. High efficiency can be difficult to achieve in these bands due to increased losses and non-ideal characteristics of the components. This target efficiency level represents a notable achievement in amplifier design, especially considering the challenges posed by higher frequencies.

2. The research paper titled **"A 14.8 dBm 20.3 dB Power Amplifier for D-band Applications in 40 nm CMOS"** by Dragan Simic et al. (2018) in IEEE Transactions on Electron Devices is mainly

focused on A new power amplifier (PA) design operating in the D-band (110-170 GHz) is introduced. This PA is fabricated using a 40 nm CMOS process and achieves a maximum power-added efficiency (PAE) of 8.9%. The PA's high output power and efficiency make it suitable for various D-band applications, including automotive radar, satellite communications, and high-speed wireless communication systems. Despite the modest PAE compared to lower-frequency designs, this achievement is significant given the challenges of operating in the D-band frequency range.

Research gap:

Manufacturing chips using 40nm technology presents challenges related to complex process variations, yield issues, and reliability concerns. As feature sizes decrease, the impact of process variations becomes more significant, necessitating stricter process control and more extensive testing.

In the production of semiconductor chips with 40nm technology, the variability in manufacturing processes can lead to difficulties in achieving consistent performance and reliability. This requires manufacturers to implement rigorous quality control measures and thorough testing procedures to ensure that the fabricated chips meet specifications and yield acceptable levels of performance and reliability.

CHAPTER IV

4.1 DESIGN SPECIFICATIONS

Parameters	**Specifications**
Frequency range	D-Band [110-170GHz] IEEE Std 802.3af-2011
Bandwidth	20GHz
Output Power	18dBm
Gain	>10dB
Return Loss	<-15dB
Drain Efficiency	75%
PAE	>62%
Device Technology	Graphene FET

CHAPTER V

5.1 DESIGN EQUATIONS

Drain current I_D can be expressed as:

$$I_{D}=q\frac{W}{L}\int_{V_{gd}}^{V_{gs}}\frac{m(x)*\mu*E(V)}{\sqrt[n]{1+\left(\frac{\mu|E(V)|}{v_{sat}}\right)^{n}}}dV \quad \text{-------------------5.1}$$

Where,

$$I_{D}=q\frac{W}{L}\int_{V_{gd}}^{V_{gs}}\frac{m(x)*\mu*E(V)}{\sqrt[n]{1+\left(\frac{\mu|E(V)|}{v_{sat}}\right)^{n}}}dV, \quad |E(V)|\approx |V_{gs}-V_{gd}|/L \quad \text{----------------------------5.2}$$

In region 1: when $V_{gs} > 0$, $V_{gd} > 0$: (electrons near S & D)

$$I_{D1}=\frac{\mu_e V_0 Q_0}{1+\left(\frac{|V_{gs}-V_{gd}|\mu_e}{Lv_{sat}}\right)}\frac{W}{L}g(\overline{V_{gs}},\overline{V_{gd}}) \quad \text{----------------------------------5.3}$$

In region 2: when $V_{gs} > 0$, $V_{gd} < 0$: (electrons near S & holes near D)

$$I_{D2}=\frac{\mu_e V_0 Q_0}{1+\left(\frac{|V_{gs}-V_{gd}|\mu_e}{Lv_{sat}}\right)}\frac{W}{L}g(\overline{V_{gs}},0)+\frac{\mu_h V_0 Q_0}{1+\left(\frac{|V_{gs}-V_{gd}|\mu_h}{Lv_{sat}}\right)}\frac{W}{L}g(0,\overline{V_{gd}}) \quad \text{-------5.4}$$

In region 3: when $V_{gs} < 0$, $V_{gd} > 0$: (holes near S & electrons near D)

$$I_{D3}=\frac{\mu_h V_0 Q_0}{1+\left(\frac{|V_{gs}-V_{gd}|\mu_h}{Lv_{sat}}\right)}\frac{W}{L}g(\overline{V_{gs}},0)+\frac{\mu_e V_0 Q_0}{1+\left(\frac{|V_{gs}-V_{gd}|\mu_e}{Lv_{sat}}\right)}\frac{W}{L}g(0,\overline{V_{gd}}) \quad \text{-----------5.5}$$

In region 4: when $V_{gs} < 0$, $V_{gd} < 0$: (holes near S & D)

$$I_{D4}=\frac{\mu_h V_0 Q_0}{1+\left(\frac{|V_{gs}-V_{gd}|\mu_h}{L v_{sat}}\right)}\frac{W}{L}g(\overline{V_{gs},\ V_{gd}}) \quad \text{------------------5.6}$$

The generalized total drain current equation:

$$I_D=I_{D1}\,S(V_{gs})S(V_{gd})+I_{D2}\,S(V_{gs})S(-V_{gd})+I_{D3}\,S(-V_{gs})S+I_{D4}\,S(-V_{gs})S(-V_{gd}) \quad \text{-----------5.7}$$

5.2 Design equations for calculating length and width of corresponding characteristic impedance

Step-1: Calculation of B

$$B=\frac{377\pi}{2Z_0\sqrt{\varepsilon_r}} \quad \text{------------------------5.8}$$

Step- 2: Calculation of width

$$\frac{W}{H}=\frac{2}{\pi}[B-1-\ln(2B-1)+\frac{\varepsilon_r-1}{2\varepsilon_r}[\ln(B-1)+0.39-\frac{0.61}{\varepsilon_r}]] \quad \text{--------5.9}$$

Step-3: Calculation of Effective dielectric constant ($\varepsilon reff$)

$$\varepsilon_{reff}=\frac{\varepsilon_r+1}{2}+\frac{\varepsilon_r-1}{2}[1+\frac{12H}{W}]^{-1/2} \quad \text{-----------5.10}$$

Step-4: Calculation of Quarter wave guided wavelength

$$\lambda_g=\frac{\lambda_0}{\sqrt{\varepsilon_{reff}}} \quad \text{----------------------------------5.11}$$

Step-5: Calculation of Length of transmission line

$$L=\frac{\lambda_g}{4} \quad \text{---5.12}$$

CHAPTER VI

6.1 ADS SOFTWARE

Fig 6.1 ADS Logo

The Advanced Design System (ADS), a piece of software for electrical design automation,is created by Path Wave Design, a division of Keysight Technologies. It provides acomprehensive design environment to designers of RF electronic devices, including mobile phones, pagers, wireless networks, satellite communications, radar systems, and high-speeddata lines. With Keysight ADS, an engineer can thoroughly characterize and optimize an RF design without switching tools. Keysight ADS includes schematic capture, layout, design rule verification, frequency-domain and time-domain circuit simulation, and electromagnetic field simulation. ADS software from Keysight has been given to various electrical engineering departments at universities. The IEEE Standard For ADS Software is IEEE 1597.1-2008.

Ads provides layout, sophisticated optimizers, and integrated system, circuit, and electromagnetic (EM) simulators to help increase productivity and efficiency while verifying high-yield designs before manufacture. Ads works with framework integration tools like mentor and cadence to fit into your design cycle.

TYPICAL PATHWAVE ADS USERS

- MMIC (Monolithic microwave integrated circuit) Designers
- Signal Integrity Engineers
- RFIC (Radio-frequency integrated circuit) Designers
- RF and Microwave Board Designers
- RF System-in-Package and RF Module Designers
- Power Electronics Designers

CHAPTER VII

7.1 EVALUATION OF GFET DEVICE FOR POWER AMPLIFIER DESIGN

The characterization and performance evaluation of a GFET (Graphene Field-Effect Transistor) device for potential application in power amplifier design. The investigation involved both theoretical calculations and DC simulations to ascertain the device's suitability for amplification purposes. The GFET was subjected to various operating conditions, including different drain voltages (V_d), gate voltages (V_g), and channel dimensions.

GFET devices have garnered significant interest in recent years due to their promising characteristics, including high carrier mobility and exceptional electrical properties. In this study, we aimed to assess the potential of a GFET device for power amplifier applications by examining its performance under different operating conditions.

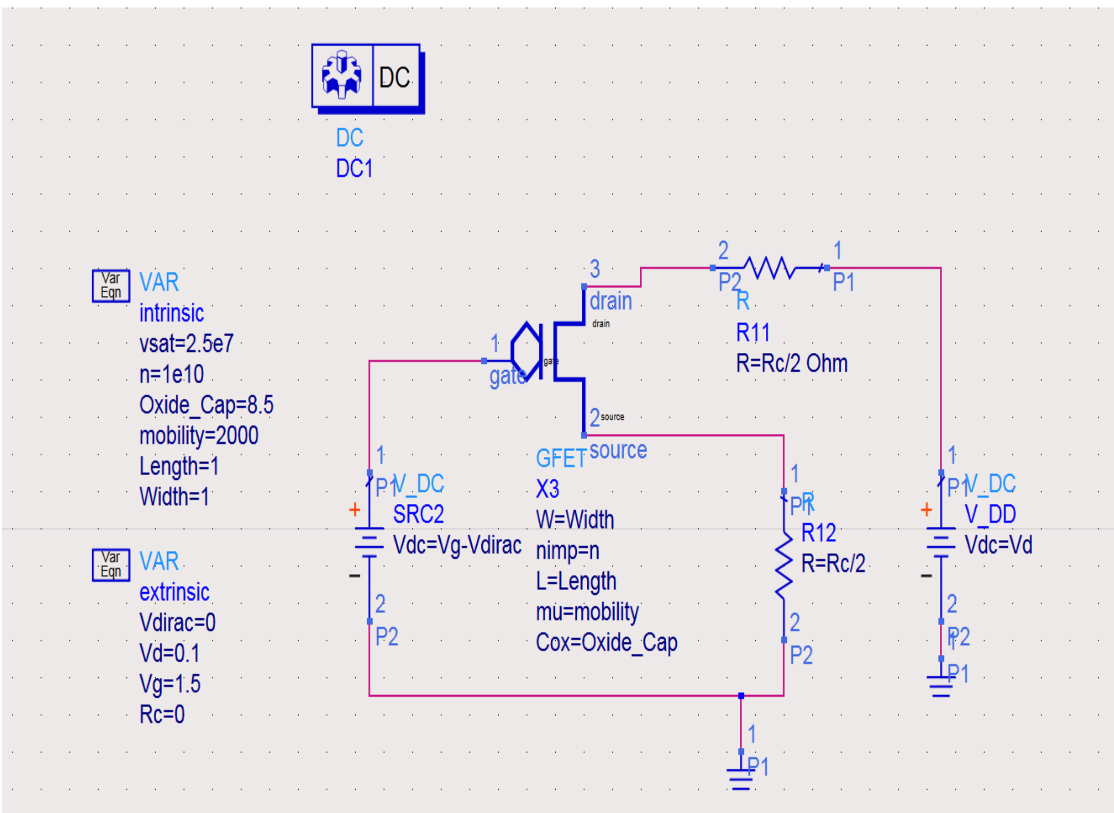

fig 7.1.a Simulation of GFET device

The GFET device under consideration was characterized using DC simulations with specific input parameters: V_d = 0.1V, V_g = 1.5V, mobility = 2000 cm^2/Vs, channel length (L) = 1µm, and channel width (W) = 1µm. Theoretical calculations were performed based on equations derived from relevant literature, and MATLAB code was developed to simulate the device behavior.

The simulated results closely matched the theoretical calculations, indicating the accuracy of the simulation model. Upon varying the drain voltage, notable changes in the drain current (I_d) were observed. When V_d was increased to 4V, the drain current exceeded 110mA, demonstrating the device's capability for high current amplification. Similarly, at V_d = 3V, the drain current surpassed 80mA, affirming the device's potential for faithful amplification.

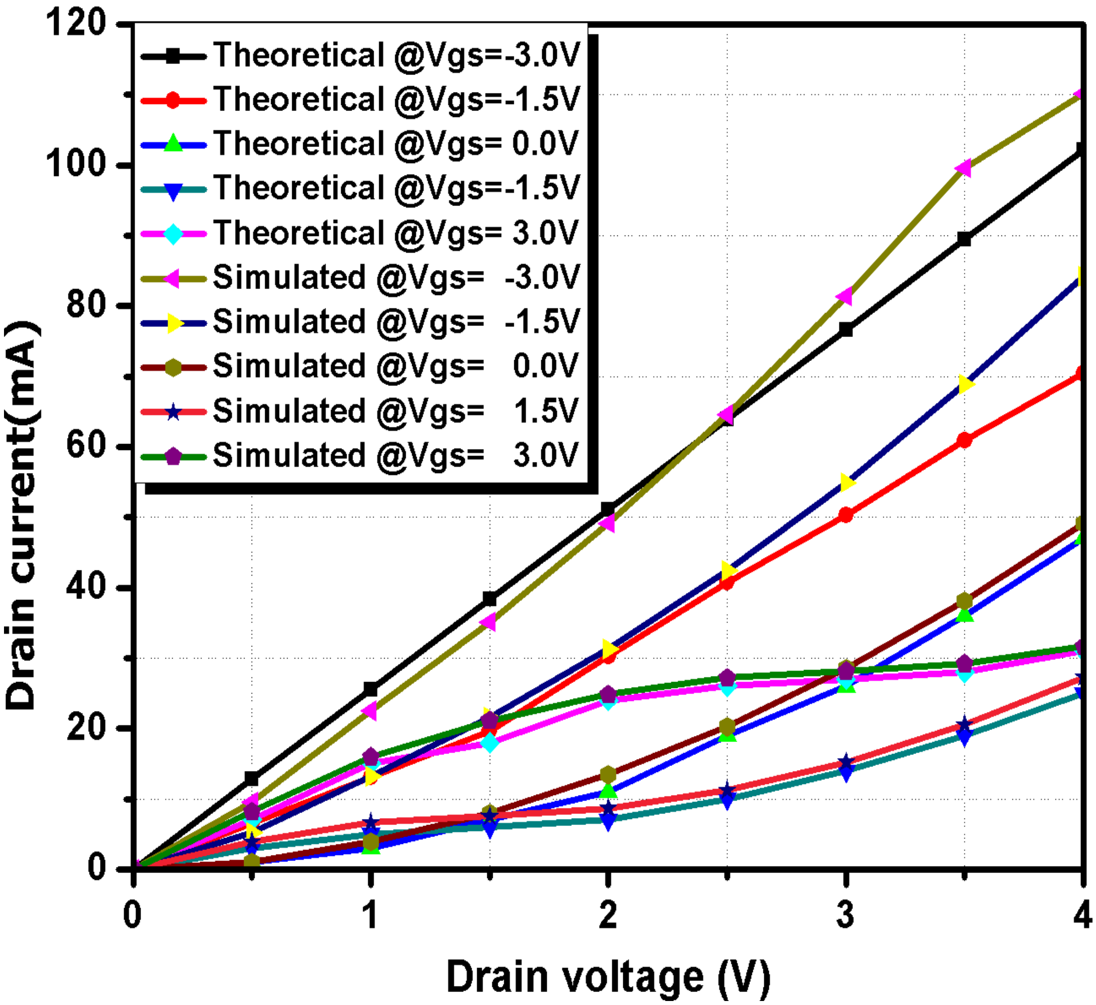

Fig 7.1.b Theoritical results

Based on the analysis conducted, it can be concluded that the GFET device exhibits favorable characteristics for power amplifier design. The observed high drain currents at elevated drain voltages suggest the device's suitability for applications requiring high gain and efficiency. Further optimization and experimentation can potentially enhance the device's performance and broaden its applicability in various electronic circuits, particularly in power amplification systems.

Future research endeavors could focus on exploring additional parameters such as temperature effects, parasitic elements, and noise characteristics to further refine the understanding of GFET behavior and optimize its performance for specific applications. Additionally, experimental validation of the device's performance under dynamic operating conditions would provide valuable insights for practical implementation in power amplifier circuits.

7.2 HIGH EFFICIENCY BROADBAND GFET POWER AMPLIFIER DESIGN

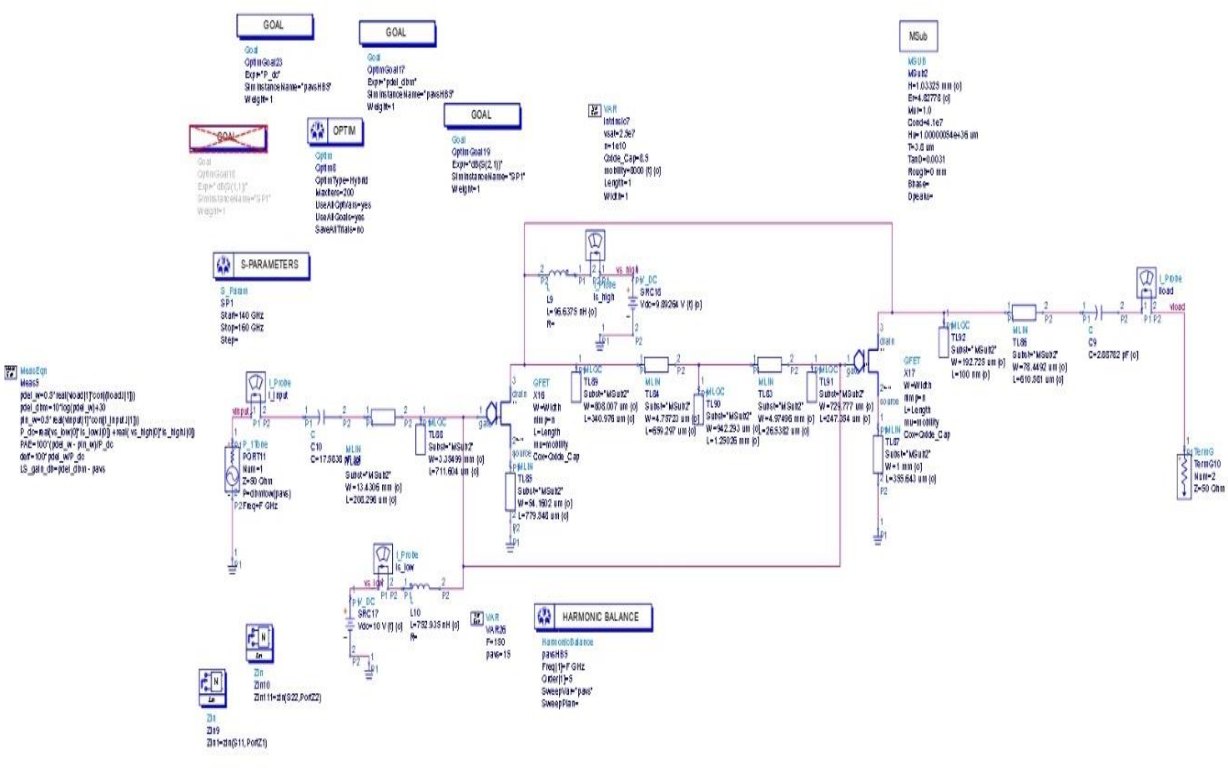

Fig. 7.2 Circuit Implementation of the proposed Class F GFET PA.

The circuit implementation the proposed Class F GFET PA with input matching network, DC biasing and output matching network is shown in Fig. 1. The proposed built-in matching technique achieves a wideband of operation, while establishing proper impedance matching. The matching technique provides real to complex impedance transformation which mitigates transmission losses at input side. A series transmission lines TL82, TL88 is employed as DC bias section GFET gate terminal to achieves a stable gain, but it effects the output impedance and degrades the overall PA bandwidth. To overcome this bandwidth loss, an output matching impedance network comprises of series transmission lines TL92, TL86 and capacitor C9. The biasing is done TL89, TL84, TL90, TL83, TL91 at gate terminal. The low device gain performance is compensated by improved power gain at D-band frequencies and thus results in overall flat gain. The series transmission lines TL92, TL86 and capacitor C9 is tuned to 140 GHz and higher harmonics at 160 GHz. This circuit Implementation follows the D-band frequency is IEEE Std: 802.3af-2011 .

7.3 MATCHING TECHNIQUES

The matching techniques that consist of Input matching network, Intermediate matching network and Output matching network.

7.3.1 INPUT MATCHING NETWORK:

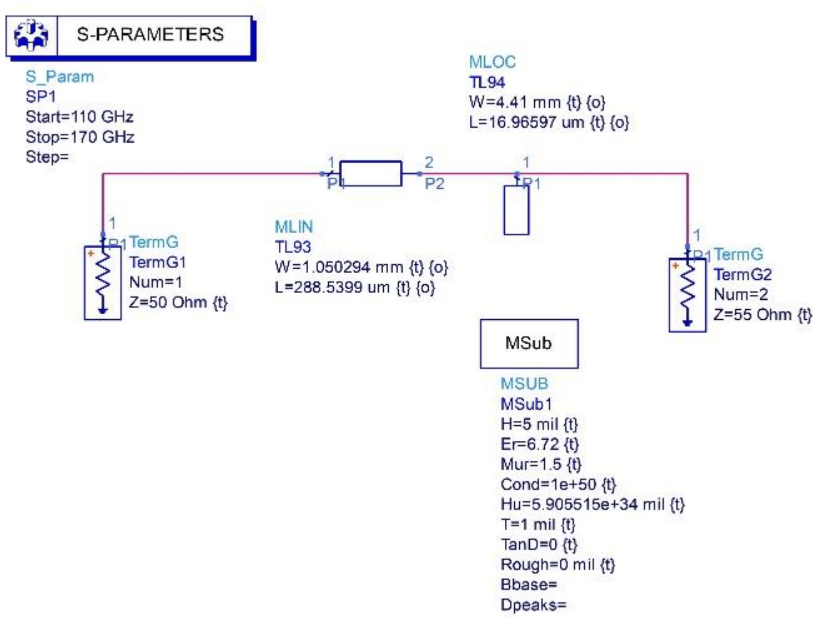

fig 7.3.1 Input matching network

This section presents the input-matching network schematic for a GFET power amplifier, designed according to the IEEE format. The network features transmission lines arranged in an inverted L-shape configuration to achieve high gain. Specifically, the transmission lines utilized are TL93 and TL94. The source impedance is set to 50 ohms to achieve proper impedance matching at the input. In the schematic diagram, components labeled as TermG1 and TermG2 represent terminations where one terminal of the component is grounded, providing a stable and low-impedance path to the ground reference of the circuit.

The behavior of the network at high frequencies, particularly within the range of 110 GHz to 170 GHz, is characterized using scattering parameters (S-parameters). These parameters are crucial for understanding the signal integrity and impedance matching of linear networks, such as amplifiers, filters, and other RF components. S-parameters provide valuable information about how much of an incident signal is reflected back from a component or circuit and how much is transmitted forward, aiding engineers in designing and optimizing impedance-matching networks to achieve maximum power transfer between components. The start and stop frequencies for the S-parameters analysis are specified as 110 GHz and 170 GHz, respectively.

The relationship btw frequency (in Hz) vs S-parameters(dB) for input matching network is:

7.3.2 INTERMEDIATE MATCHING:

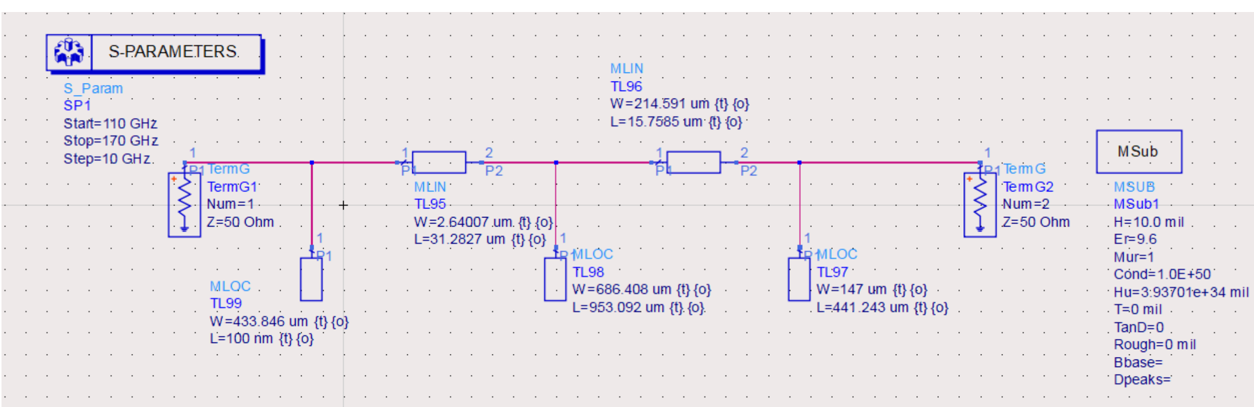

Fig 7.3.2 Intermediate matching network

This section presents the intermediate matching network schematic for a GFET power amplifier, designed according to the IEEE format. The network features transmission lines arranged in an πshape configuration to achieve high gain. Specifically, the transmission lines utilized are TL95, TL96, TL97, TL98 and TL99. The source impedance is set to 50 ohms to achieve proper impedance matching at the input. In the schematic diagram, components labeled as TermG1 and TermG2 represent terminations where one terminal of the component is grounded, providing a stable and low-impedance path to the ground reference of the circuit.

The behavior of the network at high frequencies, particularly within the range of 110 GHz to 170 GHz, is characterized using scattering parameters (S-parameters). These parameters are crucial for understanding the signal integrity and impedance matching of linear networks, such as amplifiers, filters, and other RF components.

S-parameters provide valuable information about how much of an incident signal is reflected back from a component or circuit and how much is transmitted forward, aiding engineers in designing and optimizing impedance matching networks to achieve maximum power transfer between components. The start and stop frequencies for the S-parameters analysis are specified as 110 GHz and 170 GHz, respectively.

7.3.3 OUTPUT MATCHING:

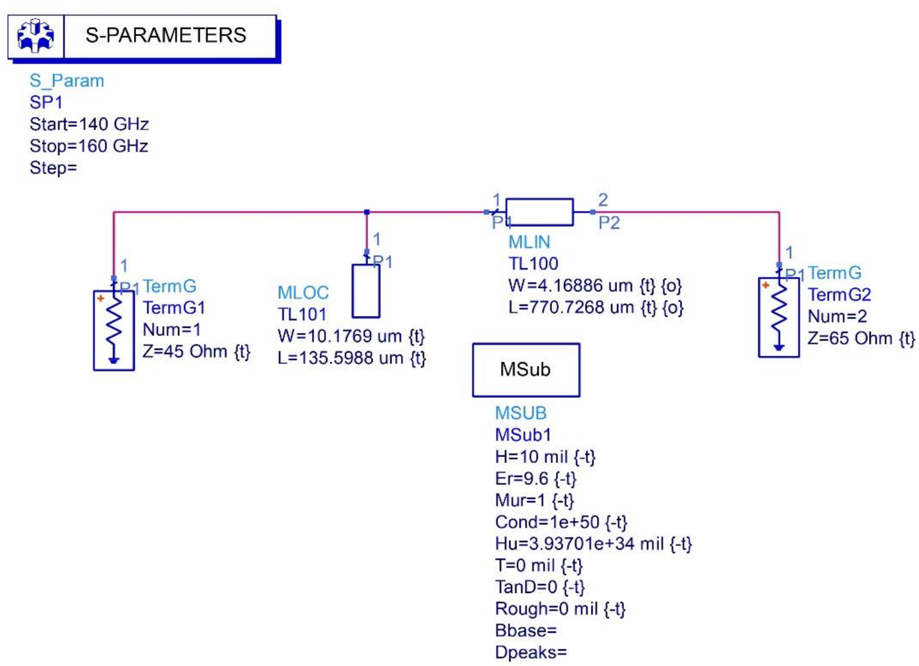

Fig 7.3.3 Output matching

This section presents the output matching network schematic for a GFET power amplifier, designed according to the IEEE format. The network features transmission lines arranged in an reversed inverted L-shape configuration to achieve high gain. Specifically, the transmission lines utilized are TL100 and TL101. The source impedance is set to 50 ohms to achieve proper impedance matching at the input. In the schematic diagram, components labeled as TermG1 and TermG2 represent terminations where one terminal of the component is grounded, providing a stable and low-impedance path to the ground reference of the circuit.

The behavior of the network at high frequencies, particularly within the range of 110 GHz to 170 GHz, is characterized using scattering parameters (S-parameters). These parameters are crucial for understanding the signal integrity and impedance matching of linear networks, such as amplifiers, filters, and other RF components.

S-parameters provide valuable information about how much of an incident signal is reflected back from a component or circuit and how much is transmitted forward, aiding engineers in designing and optimizing impedance matching networks to achieve maximum power transfer between components. The start and stop frequencies for the S-parameters analysis are specified as 110 GHz and 170 GHz, respectively.

The Circuit Implementation of the proposed Class F GFET PA Fig 7.2. The circuit is designed using two-stage common source de-generation technique. Here, we have two-stage GFET with common source topology. Input is given at the gate terminal and output is taken from drain where source is grounded.

CHAPTER VIII

8.1 RESULTS

8.1.1 Input Matching

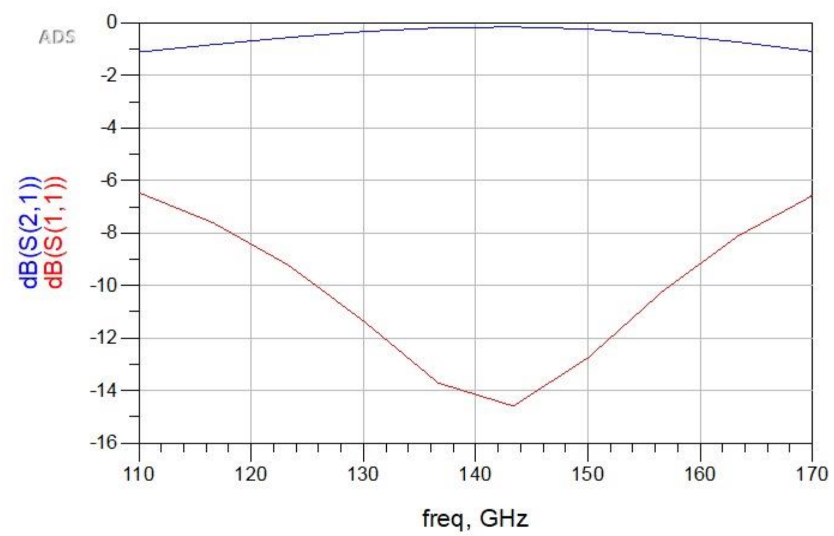

Fig 8.1.1 Input matching

The terms S(1,1) and S(2,1) refer to elements of the scattering matrix (S-parameters) used in electrical engineering and communications, particularly in the context of network analysis. S-parameters are used to describe the electrical behavior of linear electrical networks when undergoing various steady-state stimuli by electrical signals. The terms S(1,1) and S(2,1) refer to elements of the scattering matrix (S-parameters) used in electrical engineering and communications, particularly in the context of network analysis. S-parameters are used to describe the electrical behavior of linear electrical networks when undergoing various steady-state stimuli by electrical signals.

S-parameters (scattering parameters) describe how RF signals behave in a network. For a two-port network, the S-parameters are defined as follows:

S_{11}: Input port voltage reflection coefficient (also known as the return loss at port 1)

S_{21}: Forward voltage gain (also known as the insertion gain or transfer function from port 1 to port2).

S(1,1):

This parameter represents the input reflection coefficient. It indicates how much of the signal is reflected back to the input port (port 1) when a signal is applied to it.$S_{11}$is typically a complex number, indicating both magnitude and phase of the reflected signal.

The value of S_{11} should ideally be as low as possible (close to 0) for good impedance matching, which means minimal reflection and maximum power transfer. In practice, a value of S11 below -10 dB is often considered acceptable, and we have got the value S(1,1) as -15dB.

S(2,1)):

This parameter represents the forward transmission coefficient. It indicates how much of the signal passes from the input port (port 1) to the output port (port 2).S_{21} is also a complex number, representing both magnitude and phase of the transmitted signal.

The value of S_{21} should ideally be as high as possible, indicating efficient signal transmission. A value of S_{21} close to 0 dB is ideal, meaning almost all the signal is transmitted through the network, and we have got the S(2,1) value as 0dB.

8.1.2 Output Matching

The terms S(1,1) and S(2,1) refer to elements of the scattering matrix (S-parameters) used in electrical engineering and communications, particularly in the context of network analysis. S-parameters are used to describe the electrical behavior of linear electrical networks when undergoing various steady-state stimuli by electrical signals. The terms S(1,1) and S(2,1) refer to elements of the scattering matrix (S-parameters) used in electrical engineering and communications, particularly in the context of network analysis. S-parameters are used to describe the electrical behavior of linear electrical networks when undergoing various steady-state stimuli by electrical signals.

S-parameters (scattering parameters) describe how RF signals behave in a network. For a two-port network, the S-parameters are defined as follows:

S_{11}: Input port voltage reflection coefficient (also known as the return loss at port 1)

S_{21}: Forward voltage gain (also known as the insertion gain or transfer function from port 1 to port2)

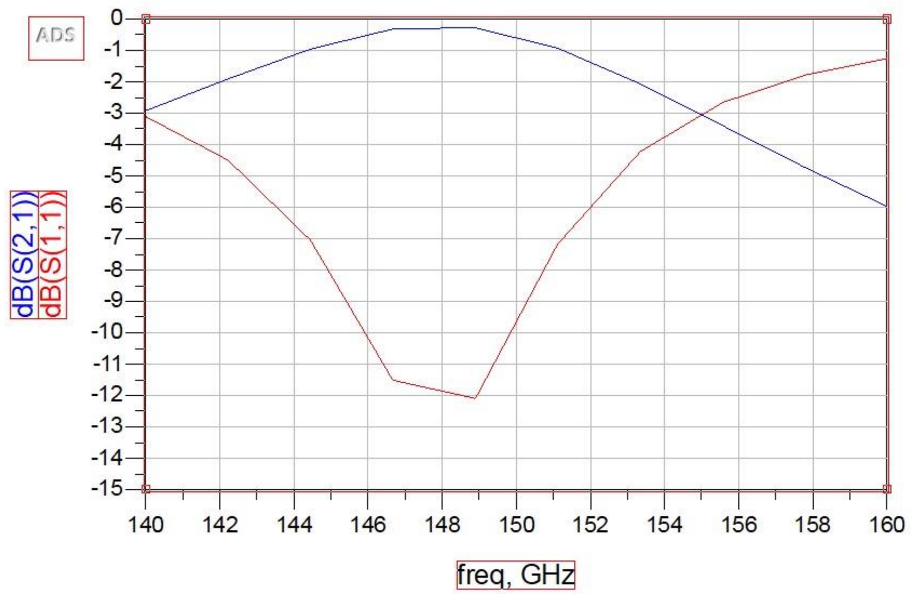

Fig 8.1.2 Output matching

S(1,1):

This parameter represents the input reflection coefficient. It indicates how much of the signal is reflected back to the input port (port 1) when a signal is applied to it.$S_{11}$is typically a complex number, indicating both magnitude and phase of the reflected signal.

The value of S_{11} should ideally be as low as possible (close to 0) for good impedance matching, which means minimal reflection and maximum power transfer. In practice, a value of S11 below -10 dB is often considered acceptable, and we have got the value S(1,1) as -12dB.

S(2,1)):

This parameter represents the forward transmission coefficient. It indicates how much of the signal passes from the input port (port 1) to the output port (port 2).S_{21} is also a complex number, representing both magnitude and phase of the transmitted signal.

The value of S_{21} should ideally be as high as possible, indicating efficient signal transmission.

A value of S_{21} close to 0 dB is ideal, meaning almost all the signal is transmitted through the network, and we have got the S(2,1) value as 0dB.

8.1.3 SIMULATED RESULTS:

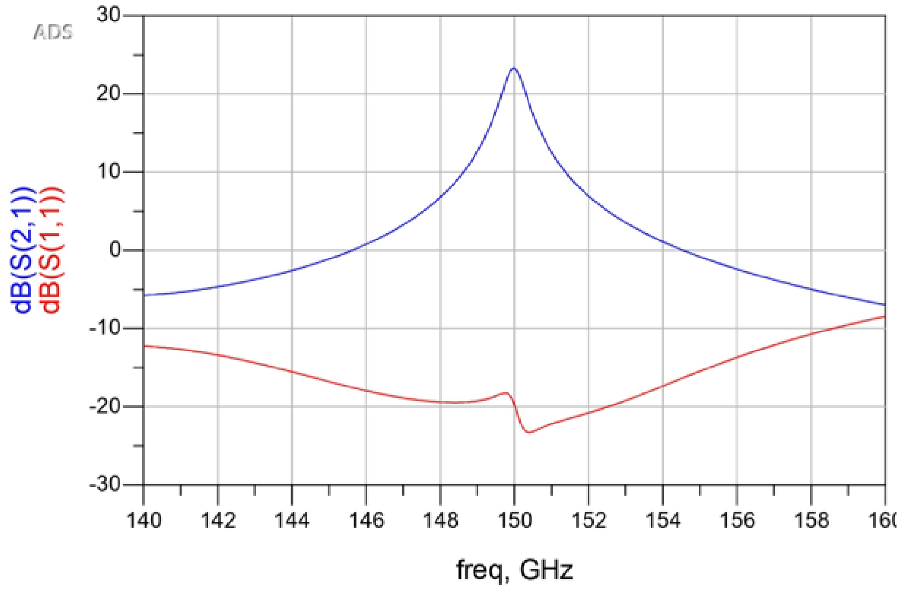

Fig 8.1.3.a Simulated results

The terms S(1,1) and S(2,1) refer to elements of the scattering matrix (S-parameters) used in electrical engineering and communications, particularly in the context of network analysis. S-parameters are used to describe the electrical behavior of linear electrical networks when undergoing various steady-state stimuli by electrical signals. The terms S(1,1) and S(2,1) refer to elements of the scattering matrix (S-parameters) used in electrical engineering and communications, particularly in the context of network analysis. S-parameters are used to describe the electrical behavior of linear electrical networks when undergoing various steady-state stimuli by electrical signals.

S-parameters (scattering parameters) describe how RF signals behave in a network. For a two-port network, the S-parameters are defined as follows:

S_{11}: Input port voltage reflection coefficient (also known as the return loss at port 1)

S_{21}: Forward voltage gain (also known as the insertion gain or transfer function from port 1 to port2)

S(1,1):

This parameter represents the input reflection coefficient. It indicates how much of the signal is reflected back to the input port (port 1) when a signal is applied to it.$S_{11}$is typically a complex number, indicating both magnitude and phase of the reflected signal.

The value of S_{11} should ideally be as low as possible (close to 0) for good impedance matching, which means minimal reflection and maximum power transfer. In practice, a value of S11 below -10 dB is often considered acceptable, and we have got the value S(1,1) as -22dB.

S(2,1)):

This parameter represents the forward transmission coefficient. It indicates how much of the signal passes from the input port (port 1) to the output port (port 2).S_{21} is also a complex number, representing both magnitude and phase of the transmitted signal.

The value of S_{21} should ideally be as high as possible, indicating efficient signal transmission. A value of S_{21} close to 0 dB is ideal, meaning almost all the signal is transmitted through the network, and we have got the S(2,1) value as 24dB.

Drain efficiency is the ratio of output RF power to the input DC power. The formula is as follows: Drain Efficiency (η) = Pout /PDC. In regards to amplifiers, efficiency is the ratio between the output power to the DC input power, and thus referred to as drain efficiency.

power added efficiency (PAE) is defined as the ratio of the difference of the output and input signal power to the DC power consumed.

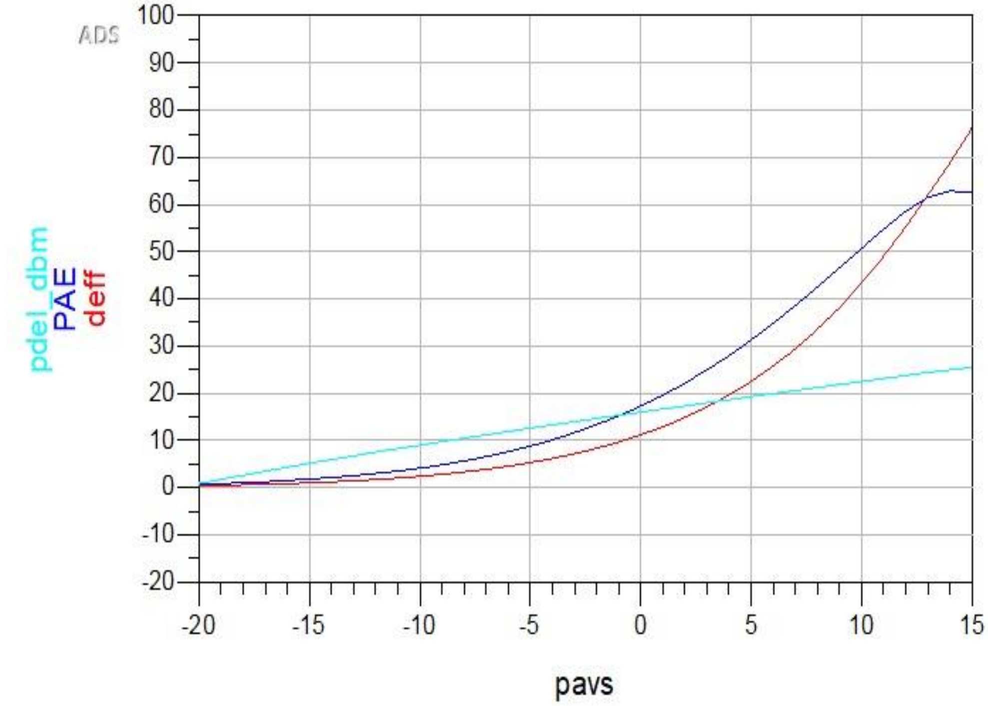

Fig 8.1.3.b Overall Simulated results

And from Fig 8.1.3.b Simulated results we got Drain Efficiency as 75%, Power Added Efficiency as 62% and Output Power as 18dBm.

CHAPTER IX

9.1 CONCLUSION

In conclusion, the development of GFET-based power amplifiers operating at D-band frequencies (110-170 GHz) marks a significant advancement in high-performance applications such as modern radar systems, high-resolution imaging technologies, and emerging 6G communication networks. GFETs, with their high electron mobility, superior carrier transport properties, and excellent thermal conductivity, offer unprecedented advantages in signal processing speed, resolution, and efficiency. These properties make GFETs ideal for addressing the challenges posed by traditional amplifier technologies, such as achieving high gain, broadband operation, and high efficiency at D-band frequencies.

The potential benefits of GFET-based amplifiers are profound, enabling ultra-high data rates and low latency required for next-generation wireless communication systems, enhancing the precision and accuracy of radar systems, and supporting detailed imaging applications in medical diagnostics and industrial inspection. By pushing the boundaries of current amplifier technology, this project aims to provide a robust, efficient, and high-performance solution tailored for D-band frequency applications. Continued research and optimization in GFET technology are essential to fully realize its potential, paving the way for innovation and advancements in telecommunications, defense, surveillance, and beyond. This effort will significantly contribute to the adoption and development of high-frequency wireless communication systems, driving the future of high-speed connectivity.

9.2 Future Scope

The future scope of GFET-based power amplifiers operating in the D-band frequency range is promising and multifaceted. As research progresses, these amplifiers are poised to revolutionize high-frequency applications across various domains. In the telecommunications sector, the development of GFET power amplifiers will be instrumental in realizing the ambitious goals of 6G networks, enabling ultra-fast data transmission, low latency, and enhanced connectivity. This advancement will support the exponential growth in data demand and facilitate new applications such as real-time holographic communication and advanced IoT ecosystems.

In radar and imaging systems, GFET-based power amplifiers will enhance performance by providing higher resolution and better accuracy. This will significantly benefit automotive and aviation industries through improved advanced driver assistance systems (ADAS) and autonomous navigation, while also advancing medical diagnostics and security scanning with superior imaging capabilities.

Continued innovation in GFET technology is expected to yield improvements in amplifier efficiency, gain, and bandwidth, further optimizing performance at D-band frequencies. Additionally, the exploration of integration techniques and materials compatible with GFETs will expand their applicability and reliability in commercial and military applications. Overall, GFET-based amplifiers are set to play a crucial role in the next generation of high-speed communication and sensor technologies, driving forward technological progress and industrial innovation.

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