PROJECT DEFINITION DOCUMENT

DESIGN & DEVELOPMENT OF ACTIVE INTEGRATED ANTENNA (AIA) WITH POWER AMPLIFIER (PA)

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Chapter 1

Introduction to the Project

1.1 Project Title

The title of the FYD Project is "Design and Development of Active Integrated Antenna with Power Amplifier (PA) of 10-Watts for 5G Applications".

1.2 Project Statement

To design, simulate, fabricate and test of 10-Watts Active Integrated Antenna with Power Amplifier (PA). The aim is to design the integrated system for a wideband range of frequencies. The system would be provided with a very low signal input power of 1mW (0 dB). The design and the prototype would be used in various RF based projects, and more likely in the 5G communication systems.

1.3 Scope of the Project

In the recent era, with the ongoing evolution of the 5G technology, there is a very extensive room for the hardware development related to 5G communications. The integration of an active antenna with a power amplifier enhances the overall performance of the communication system. The diagram of RF signal flow using a Power Amplifier with an integrated antenna is shown below. In this project designing an efficient Power Amplifier (PA) would be the focus along with the efficient integration of active antenna. The Power Amplifier is aimed to be a wideband system with targeted 5G band of "n77", having frequency range from 3.3 GHz to 4.2 GHz. Power Amplifiers play a critical role in signal amplification, which is the utmost requirement in wireless communication systems. Through this PA, we would be able to receive the minimum power required for reliable communications, and hence designing it optimally and efficiently would address the challenges. Furthermore, integrated antenna would be a more practical solution to the problem as it reduces the cost of separate systems to the cost of increased complexity. This project targets the 5G communication which does not have a fully matured hardware available, and therefore the 5G industry can benefit from this innovative solution that enhance the performance of 5G networks. The Advanced System Design (ADS) software would be used to simulate the design.

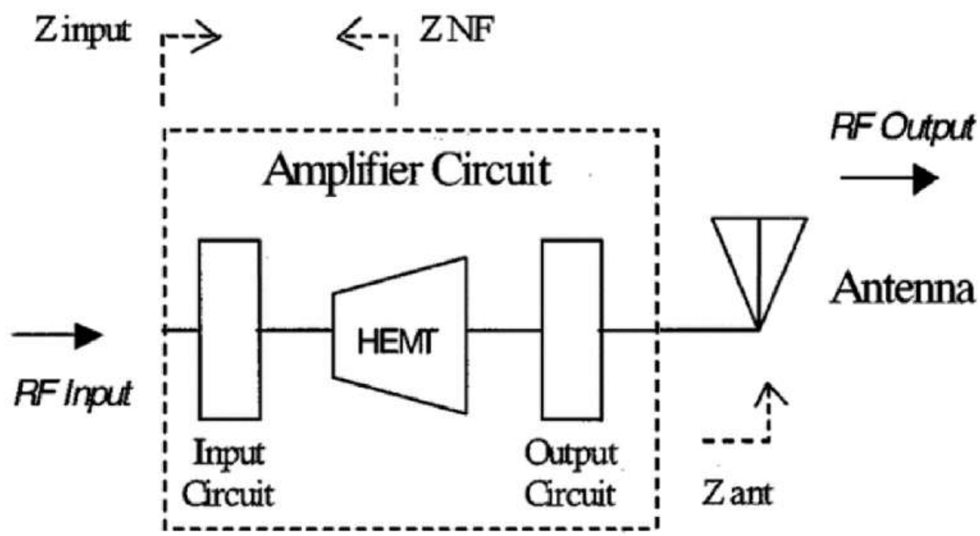

Figure 1.1: Block diagram of Active Antenna integrated with PA.

Chapter 2

Literature Review

An Electronic device that increases the power of the input RF signal is called Power Amplifier (PA), and Active Antenna refers to the integrated Antenna with Power Amplifier. For a front-end RF application, a weak signal is generated at the source which reproduces the signal with a stronger output by using an external power source and feeds it into Active Antenna.

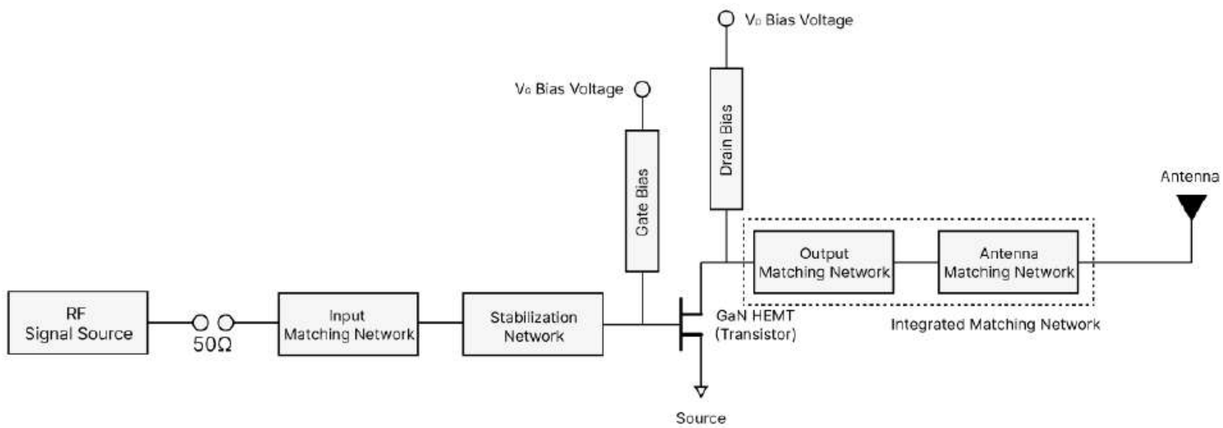

Figure 2.1: Block Diagram of RF Front End – PA with Integrated Antenna

There are different types of Amplifiers that are provided below:

1. Small Signal Amplifier
2. Large Signal Amplifier
3. Power Amplifier
4. Low Noise Amplifier
5. Max Gain Amplifier

For the complete task, we would aim to design a power amplifier having the optimum PAE (Power Added Efficiency) and then move on to the design and integration of the Antenna (which is discussed later). The power amplifier is aimed to have 10 watts power output, by having a very low power signal as input.

2.1 Basics of Power Amplifier

Average Power is the product of voltage and current it is represented in two domains one is the frequency domain and other is the time domain. Average Power in frequency domain is shown below:

$$P_{avg} = \frac{1}{2} VI \qquad (Eq\ 1)$$

Average power in Time domain is shown below:

$$P_{avg} = \frac{1}{T} \int_0^T v(t) * i(t)\, dt \qquad (Eq\ 2)$$

Where;

$$v(t) = Vp * sin(\omega t) \qquad (3\ Eq)$$

$$i(t) = Ip * sin(\omega t + \varphi) \qquad (\ Eq\ 4)$$

After putting $(Eq\ 3)$ and $(Eq\ 4)$ in $(Eq\ 2)$ and simplifying them we will get.

$$P_{avg} = \frac{1}{2} V_p\, I_p\, cos(\varphi) \qquad (Eq\ 5)$$

By using this relation, we will get both DC and RF power. As we know.

$$Vp = \frac{1}{2} V_{pp} \qquad (6\ Eq)$$

$$Ip = \frac{1}{2} I_{pp} \qquad (7\ Eq)$$

After putting $(Eq\ 6)$ and $(Eq\ 7)$ in $(Eq\ 5)$ and simplifying them we will get.

$$P_{avg} = \frac{1}{8} V_{pp}\, I_{pp}\, cos\ (\varphi\ )$$

By using these mathematical relations, we can calculate the RF power.

2.2 5G Band Power Amplifier

Designing the power amplifier for the major part depends on the target frequency band. In this project we are focusing on the n77 – Band (5G) used for the wireless communications having matured communication and networking protocols. The n77 – Band is used for both uplink and downlink 5G communications. The frequency range of the n77-band is from $3.3\ GHz - 4.2\ GHz$.

2.3 Background

The triode vacuum tube was the first device that can amplify the signal. It was invented by Lee De Forest in 1906 by using it in 1912 first amplifier was designed. From 1960 to 1970 Triode vacuum tubes were used in all amplifiers. In the start, power amplifier was made by using a vacuum tube even the first AM radio was built with a triode vacuum tube amplifier. To extend the transmission of radio signals over increasingly long-distance Triode vacuum tubes were used to amplify the amplitude of the electrical signal. Today transistors are being used instead of Triode vacuum tubes.

Figure 2.2: Triode Vacuum Tube

2.4 Transistor Technology

Transistors are semiconductor devices with three (and sometimes more) terminals. The third terminal enables output current to be controlled by a relatively small and low-power input signal. In amplifiers, transistors are used to achieve current gain, voltage gain, or power gain. Most often power gain is the objective in RF and microwave design.

There are three fundamental types of microwave transistors [5, 6]: bipolar junction transistors, (BJTs); junction field effect transistors, (JFETs); and insulated gate FETs, (IGFETs), with the metal-oxide-semiconductor FETs, (MOSFETs), being the most common type of IGFET. The three fundamental types of transistors are considered in the following subsections.

2.4.1 BJT and HBT

A bipolar transistor has three semiconductor regions called the collector (C), base (B), and emitter (E), as shown in the BJT cross section of Figure 1.4. An NPN BJT has n-type semiconductor at the emitter and collector, and p-type semiconductor forms the base. In this transistor, the positive sense of current flow is from the collector through the base to the emitter and the dominant carriers in the p-type base region are electrons, and so this is called a minority carrier device.

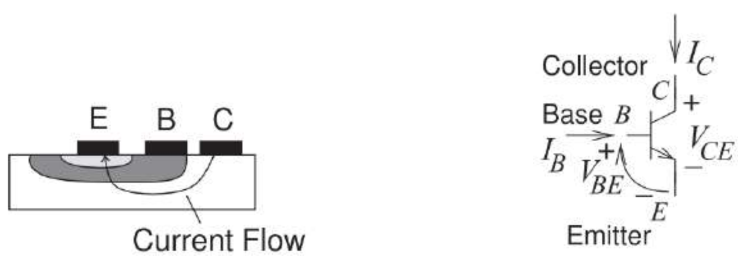

Figure 2.3-2.4: Cross Section of BJT & Symbology of BJT.

When realized in silicon, a bipolar transistor is called a bipolar junction transistor, (BJT); and in compound semiconductor technology it is a heterostructure bipolar transistor, (HBT). In a silicon germanium (SiGe) BJT transistor, germanium is normally used to increase the hole and electron mobility and the device is not regarded as a compound semiconductor transistor.

2.4.2 MOSFET

MOSFET stands for Metal Oxide Semiconductor Field Effective Transistor. There are several types of FETs, with the MOSFET being the most common. With all FETs there is a channel between two terminals, the source and drain, and an applied field produced by a voltage at a third terminal, the gate, controls the cross section of the channel and the number of carriers in the channel. Hence the gate voltage controls the current flow between the drain and the source.

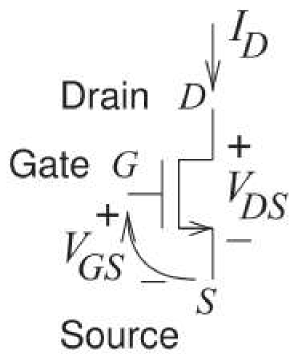

Figure 2.5: Symbology of MOSFET.

A very fundamental characteristic of a Transistor lies in its I-V (also known as input-output characteristics) characteristics, this helps us recognize the ability of the transistor to amplify any given signal, also helps us differentiate the limitations and capabilities of transistors. The linear region is sometimes (but less often) called the triode region because of similarity to the characteristics of the triode vacuum tube device. Similarly, the saturation region is sometimes called the pentode region.

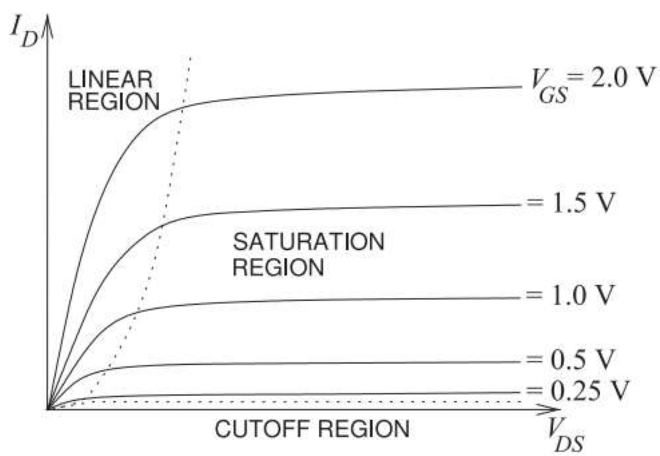

Figure 2.6: I-V Characteristics and Regions of nMOS

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2.4.3 MESFET, HEMT, and JFET

The MESFET (Metal Semiconductor Field Effective Transistor) and HEMT (High Electron Mobility Transistor) are types of JFETs (Junction Field Effective Transistor) fabricated using compound semiconductors, with JFET most commonly referring to silicon devices only. With the silicon JFET, the voltage applied to the gate terminal changes the amount of reverse bias and hence the depletion region thickness. Increased reverse bias reduces the cross section of the current-carrying channel. Thus, a JFET looks like a variable conductance.

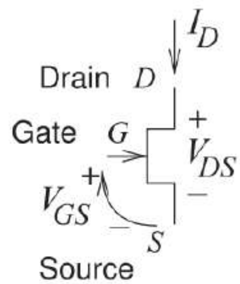

Figure 2.7: Symbology of JFET.

A device like the MESFET is the high electron mobility transistor (HEMT), where the field is established at the junction of two compound semiconductor materials having different band gaps, called a heterojunction. The channel is formed at the heterojunction. The HEMT is also called the heterostructure FET (HFET). A MESFET with a graded junction is called a modulation-doped FET (MODFET).

2.5 Comparison of GaN HEMT

GaN HEMT stands for Gallium Nitrate High Electron Mobility transistor. For accomplishing this project GaN HEMT transistor is selected because it has high output power density. As per the literature available it has been very evident in the RF technology that GaN is able to provide Higher efficiency and wider bandwidth by having higher power density. As shown in table 2.1 GaN has higher power density, so it has improved DC to RF efficiency. As compared to other semiconductor technologies GaN provides us with better efficiency, thermal performance, and gain. It has a high operational voltage of 4 times more output power than can be obtained by using GaN as compared to GaAs transistors of the same size.[6], [7], [8], [9].

Table 2.1: Comparison of GaN with Si, SiC and GaAs

PROPERTIES	GaN	Si	SiC	GaAs
Power Density (W/mm)	7	0.8	4	1.5
Bandgap (eV)	3.4	1.12	3.2	1.4
Breakdown field (mv/cm)	3.3	0.3	3.5	0.4
Electron Mobility $[cm^2/\ V\ s]$	2000	1500	650	8500
Hole Mobility $[cm^2/\ V\ s]$	300	480	120	400
Saturation electron drift Velocity (cm/s)	$2.5*10^7$	10^7	$2.7*10^7$	$1.2*10^7$
Transit Frequency (GHz)	150	20	20	150
Dielectric Constant	9.5	11.9	10	12.5
Thermal Conductivity (W/mC)	130	150	450	550

2.5.1 GaN HEMT

GaN High Electron Mobility Transistor is the focus for the design of the power amplifier in this project. The available packages in the market have an operating voltage of 28-volts, and is a general purpose packaged discrete transistor. GaN HEMTs offer high efficiency, high gain and wide bandwidth capabilities making it ideal for linear and compressed amplifier circuits. The specifications for the frequency range or the frequency band we are targeting in the project should meet some standards mentioned below.

- Up to 6 GHz Operation
- 16 dB Small Signal Gain at 2.0 GHz
- 14 dB Small Signal Gain at 4.0 GHz
- 13 W typical P_{SAT}
- 65 % Efficiency at P_{SAT}
- 28 V Operation

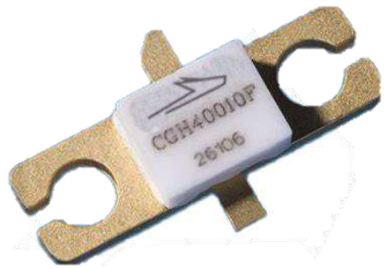

Figure 2.8: CGH40010P GaN HEMT (Wolfspeed's package).

2.6 Performance Parameters of Power Amplifier

The primary goal of a power amplifier is to achieve maximum output power. Efficiency, power dissipation capability and signal to noise ratio are the most important performance parameters of a power amplifier (PA).

2.6.1 Efficiency

Efficiency explains how well an amplifier converts direct current power to alternating current power. The ratio of maximum RF output power to the DC power supplied by the battery of a power amplifier is known as circuit efficiency.

$$\eta = \frac{Maximum\ RF\ Output\ Power}{DC\ Power\ Supplied\ by\ Battery}$$

Another term which is wide used in the RF is of Power Added Efficiency or PAE. It is the ratio of change in average ac power from output to input to average dc power drawn by the circuitry. It accounts for the RF input power.

$$\eta_{PAE} = \frac{P_o(RF) - P_{in}(RF)}{P_{in}(dc)}$$

Hence, the higher the PAE, the better the power amplifier in terms of efficiency.

2.6.2 Signal Distortion

Signal distortion is a critical factor in determining the quality and reliability of amplified signals. Signal distortion in a power amplifier refers to any alteration or deviation of the output signal from the original input signal. This distortion can manifest as harmonic distortion, intermodulation distortion, or other non-linear effects. Harmonic distortion introduces unwanted frequency components, while intermodulation distortion creates undesired signal combinations. Lower distortion values indicate better amplifier linearity and fidelity, ensuring that the amplified signal closely matches the input, a crucial consideration in applications where signal integrity is paramount, such as high-quality audio reproduction or precision communication systems.

2.6.3 Power Dissipation Capability

The ability of the transistor to dissipate the heat is called power dissipation capability. It is also known as the power rating of the transistor. In the power transistor an excessive number of current flows because of which a large amount of heat dissipated. Because of this heat, the temperature of the transistor changes which can affect the working of the transistor by changing the operating point of the transistor. If the amount of heat dissipated from the transistor is greater than the ideal power rating. Then the transistor is likely to burn out and hence to increase the power dissipation capability of the transistor we can connect a metal piece called a heat sink.

The heat sink provides a larger area so that more heat moves from the transistor into surrounding space to prevent the transistor from burning out. In this way, we can increase the power dissipation capability of the transistor.

2.6.4 1 dB Compression Point

1 dB compression point is the output level at which the gain decreases by 1 dB from its desired value. Once an amplifier reaches its $P_{1\,dB}$ it goes into compression and becomes a non-linear device, producing distortion, harmonics and intermodulation products. The amplifier should always be operated below the compression point.

$$High\ P_{1\,dB} \rightarrow High\ Linearity \rightarrow Better\ Power\ Amplifier$$

3 Top of Form

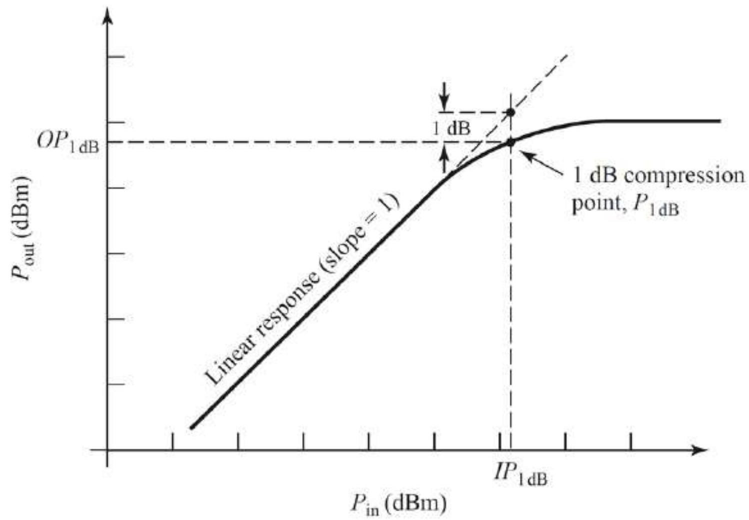

Figure 2.9: 1 dB Compression Point

Related to the 1 dB compression point, it is very vital to understand about the Dynamic Range of the transistor or amplifier. It is the Range of the output power in which the device behaves as the linear device. Hence, while designing the power amplifier in this project we shall operate in the linear region.

2.6.5 Load Pull Contours

Load pull contours are graphical representations that depict the performance of an RF power amplifier under varying load conditions. These contours illustrate how the amplifier behaves in terms of power, efficiency, and other parameters across different complex load impedances.

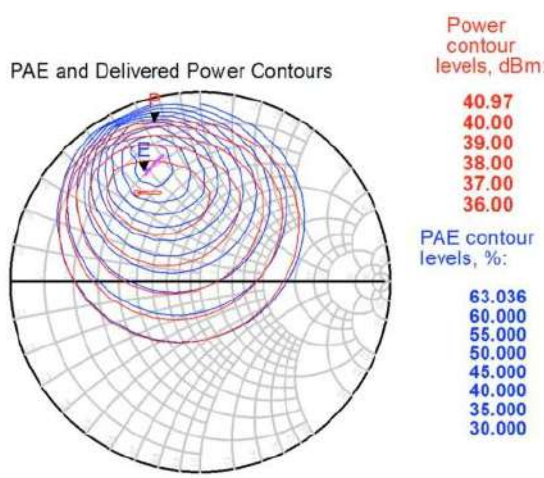

Figure 2.10: Load Pull Contours

The load pull technique involves adjusting the impedance at the output (load) of the amplifier while measuring its performance metrics, such as output power and efficiency. Load pull contours are then generated to visualize how these metrics change across different load impedance values. By examining load pull contours, designers can identify the optimal load impedance for maximizing power, efficiency, or other desired parameters, tailoring the amplifier for specific applications or frequency bands. This technique is particularly important in designing power amplifiers for wireless communication systems, where the impedance matching is crucial for achieving optimal performance.

2.6.6 Signal-to-Noise Ratio

The ratio of signal power to noise power is known as the signal-to-noise ratio. Better performance will be achieved if a higher signal-to-noise ratio is available. In signal-to-noise, all unwanted signals variation is represented by the term noise. The movement of charged carriers in the passive components of the circuit causes thermal noise. In transistors, the random arrival of charge carries around the potential barrier causing shot noise.

$$SNR = \frac{P\ (Signal)}{P\ (Noise)}$$

2.7 Amplifier Classes

Based on the mode of operation, amplifiers are categorized into classes, such as class A, class B, class C, class AB and so on.

2.7.1 Class A Operation

An amplifier that can conduct during the full cycle of input signal or it has 360 degrees of conduction is called a class A power amplifier. Due to the low level of signal distortion, it is considered the most common type of power amplifier. Generally, it is not used for high-power applications. Class A power amplifier has some characteristics like low signal distortion level. Because of element bias, this device always conducts. It is quite stable. It has the highest linearity. It has an efficiency of vicinity 25-50% which is very low. As it operates throughout the operation that's why during operation it has high heat output.

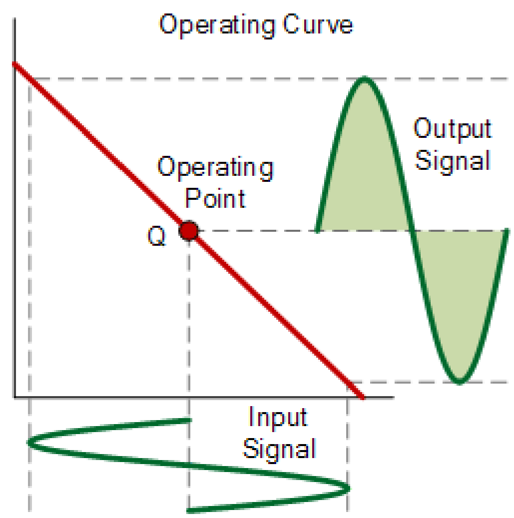

Figure 2.11: Class A Amplifier Operation

2.7.2 Class B Operation

Amplifiers that can conduct half of the input signal cycle is called class B power amplifier. It is having 180-degree conduction angle. It means that it can amplify only half of the input cycle. It consists of two transistors one works for only the positive cycle of input signal and other works only for the negative cycle of the input signal. They amplify positive and negative input cycles respectively which will combine to form a complete signal. Compared to a class A power amplifier, it has some advantages and disadvantages. It has some characteristics like it is having an efficiency in a range of 78.5% which is much higher as compared to class A power amplifiers. It produces less heat. It is stable and reliable. One complete amplified signal is formed from the combination of two half amplified signals.

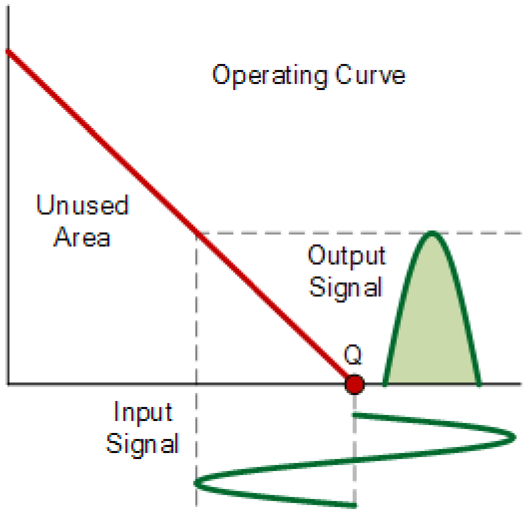

Figure 2.12: Class B Amplifier Operation

2.7.3 Class AB Operation

Class A and Class B power amplifiers combine to form class AB power amplifier. As it is clear from the name that class AB power amplifier is a mix of class A and class B power amplifiers. It consists of two conducting elements called transistors and both run at the same time. This thing helps in covering the “dead zone” as it was seen in the class B power amplifier. Class AB amplifiers have conduction angles from 180-360 degrees, and generally operate around 245 degrees which generates the maximum output power. The efficiency corresponding to this point is 65%.

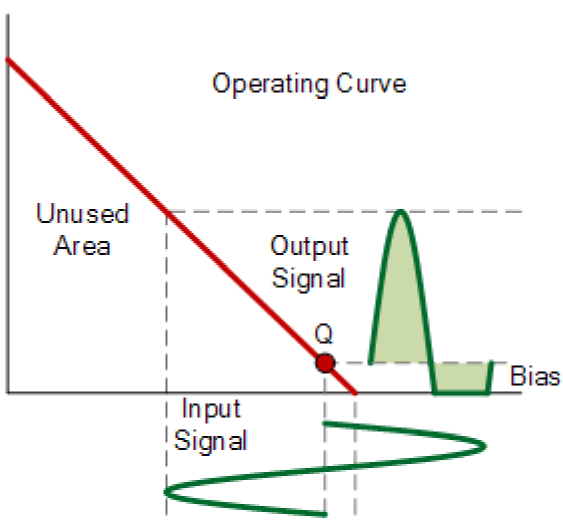

Figure 2.13: Class AB Amplifier Operation

2.7.4 Class C Operation

It's very efficient. It is having lowest operating cycle, and it also has the lowest linearity. Less than half of an input cycle, it stays on because it is heavily doped. It has a conduction angle of less than 180 degrees. Because of this conduction angle it is having high efficiency but because of having the lowest linearity. It is used in such applications where high efficiency is required, like in radio frequency applications. It dissipates less power.

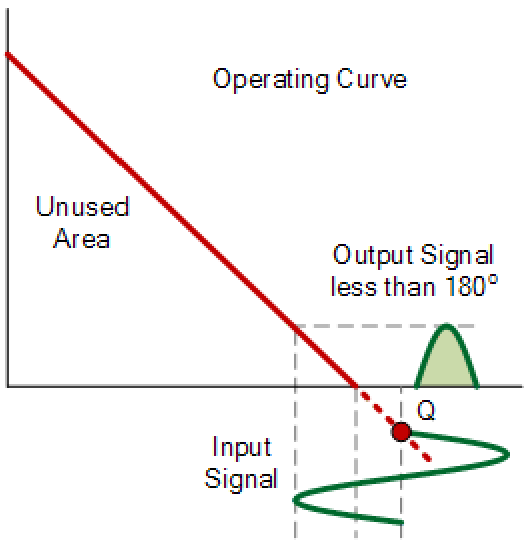

Figure 2.14: Class C Amplifier Operation

2.8 Comparison of Amplifier Classes

Different classes of Power Amplifier (PA) are shown in table 2.1. Class B is having good efficiency as compared to Class A and Class AB Power Amplifier (PA), but Class B has poor linearity like Class D, E, Fand Class J Power Amplifier (PA). On another side while comparing the Class A and Class AB power amplifiers. It is clear in table 2.1 that Class A has excellent linearity, but it has lower efficiency as compared to Class AB Power Amplifier. So, Class AB is finalized for this project.

Table 2.2: Classes of Power Amplifier

Sr. No.	CLASSES OF POWER AMPLIFIER	EFFICIENY (%)	LINEARITY	CONDUCTION ANGLE (degrees)
1	Class A	50%	Excellent	360^o
2	Class B	78.5%	Poor	180^o
3	Class AB	65%	Good	180^o-360^o
4	Class C	100%	Worst	0^o
5	Class D	100%	Poor	0^o
6	Class E	100%	Poor	0^o
7	Class F	100%	Poor	0^o
8	Class J	100%	Poor	0^o

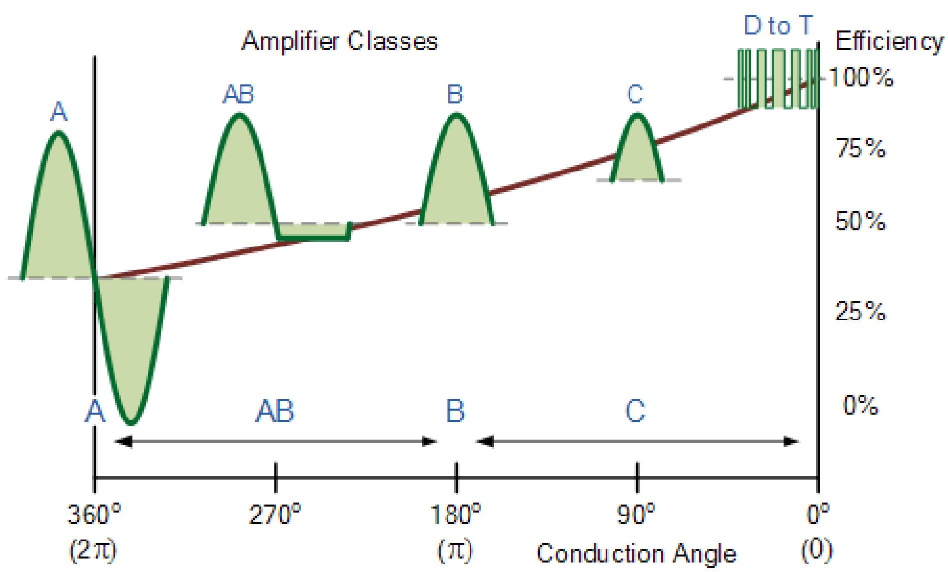

Figure 2.15: Comparison of Amplifier Classes

2.9 Antenna

An antenna is defined by Webster's Dictionary as "a usually metallic device (as a rod or wire) for radiating or receiving radio waves." Additionally, the antenna or aerial as "a means for radiating or receiving radio waves." It acts as the transitional structure between free-space and a guiding device. The guiding device or transmission line may take the form of a coaxial line or a hollow pipe (waveguide), and it is used to transport electromagnetic energy from the transmitting source to the antenna, or from the antenna to the receiver. The antenna includes whole circuitry having its source, its transmission line and the physical antenna part. The Thevenin equivalent circuit is shown.

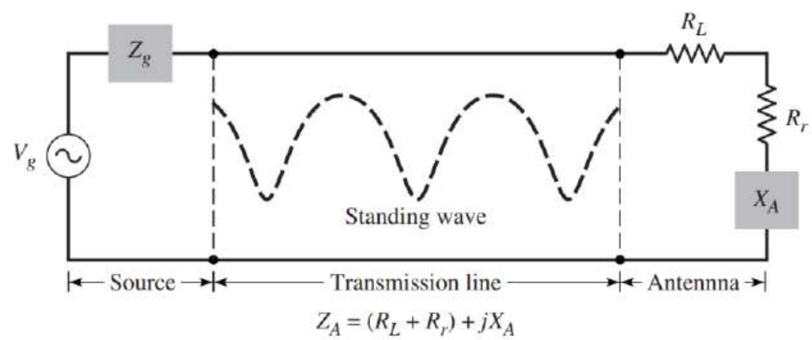

Figure 2.16: Thevenin Equivalent circuit of Antenna

2.9.1 Active Antenna

An Active antenna is a type of antenna that incorporates active electronic components, typically an integrated amplifier, to enhance its performance. Unlike passive antennas that rely solely on their physical structure to receive or transmit signals, active antennas actively amplify or process the incoming or outgoing signals. The integration of amplification components within the antenna itself helps overcome signal losses and improve overall system performance, especially in scenarios with long cable runs or weak signal environments.

In the Active Antenna, where in our case the Power Amplifier is the active part, we must design the compatible matching circuit for the integration as well. This is one of the major components of the RF system to achieve the best SNR transmission over free space.

2.9 Types of Antennas

There are different types of Antennas that have been designed in the respective field. The major types of Antennas are provided below.

2.10.1 Wire Antennas

Wire antennas are a type of antenna that uses conductive wire elements to transmit or receive radio frequency signals. These antennas are fundamental and widely used due to their simplicity, cost-effectiveness, and versatility. Various types of wire antennas exist, each with specific characteristics and applications. Some common types include:

(a) Dipole Antenna

- Consists of two equal-length conductors extending in opposite directions from a central feed point. Dipole antennas are resonant and widely used for their simplicity and efficiency.

Figure 2.17: Dipole Antenna

(b) Monopole Antenna

(c) Loop Antenna

(d) Helix / Helical Antenna

(e) Yagi-Uda Antenna

2.10.2 Aperture Antennas

Aperture antennas may be more familiar to the layman today than in the past because of the increasing demand for more sophisticated forms of antennas and the utilization of higher frequencies. Antennas of this type are very useful for aircraft and spacecraft applications because they can be very conveniently flush-mounted on the skin of the aircraft or spacecraft. In addition, they can be covered with a dielectric material to protect them from hazardous conditions of the environment.

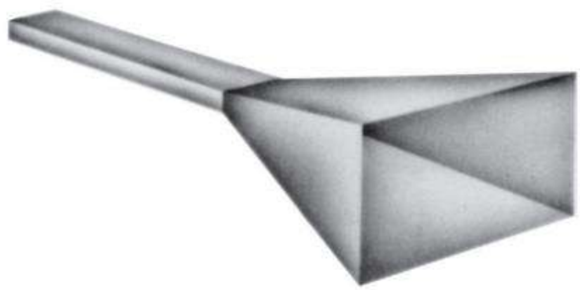

Figure 2.18: Pyramidal Horn Aperture Antenna

2.10.3 Microstrip Antennas

A microstrip antenna is a type of planar antenna that consists of a flat conducting strip, usually made of copper, printed, or etched on a dielectric substrate. This configuration creates a low-profile and lightweight structure, making microstrip antennas suitable for integration into various electronic devices, such as mobile phones and wireless communication systems. The substrate serves as both a supporting material and a dielectric, determining the antenna’s electrical properties. Microstrip antennas can take various shapes, including rectangular patches or more complex geometries, and their design allows for flexibility in achieving specific frequency characteristics. These antennas are popular due to their ease of fabrication, low cost, and versatility, although they may exhibit some bandwidth limitations compared to other antenna types.

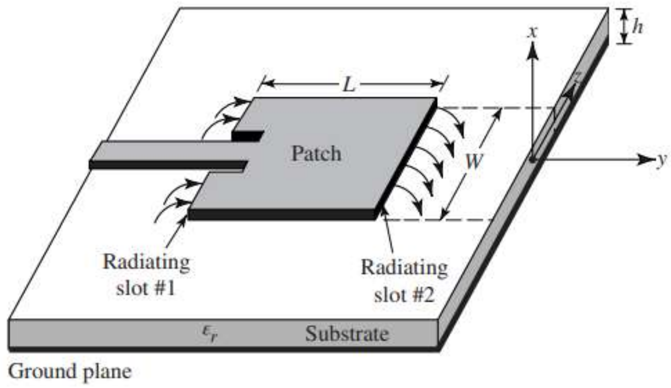

Figure 2.19: Microstrip Patch Antenna

These types of Antennas are widely used in prototype applications such as in this project. The ease of fabrication for these antennas on the substrate makes them integrated with the Power Amplifiers (PA). Considering the available facilities in the college, it is more feasible to design a Microstrip Antenna for this project.

2.10.3.1 Array Antennas

A microstrip array antenna is a configuration of multiple microstrip antennas arranged in a systematic pattern to collectively form an array. Each microstrip element within the array contributes to the overall antenna's performance. Microstrip array antennas are known for their directional characteristics, high gain, and beamforming capabilities.

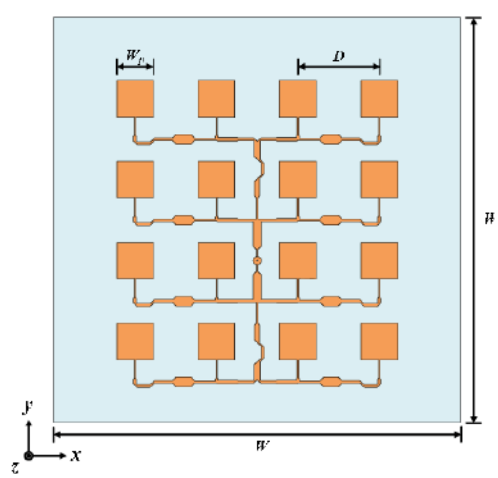

Figure 2.20: Microstrip Array Antenna

2.10.3.2 SIW Antennas

A Substrate Integrated Waveguide (SIW) antenna is a type of planar antenna that combines the principles of traditional waveguide structures with the advantages of planar technology. It is formed by integrating a waveguide structure into a planar dielectric substrate, creating a compact and lightweight antenna. SIW antennas offer characteristics such as low loss, high efficiency, and the ability to support multiple frequency bands. The substrate acts as a supporting material and dielectric medium, while the integrated waveguide structure guides the electromagnetic waves. SIW antennas are commonly used in applications like satellite communication, radar systems, and wireless networks where their planar form factor and performance attributes are advantageous. Hence, for this project a feasible option for the Antenna part is designing SIW antenna.

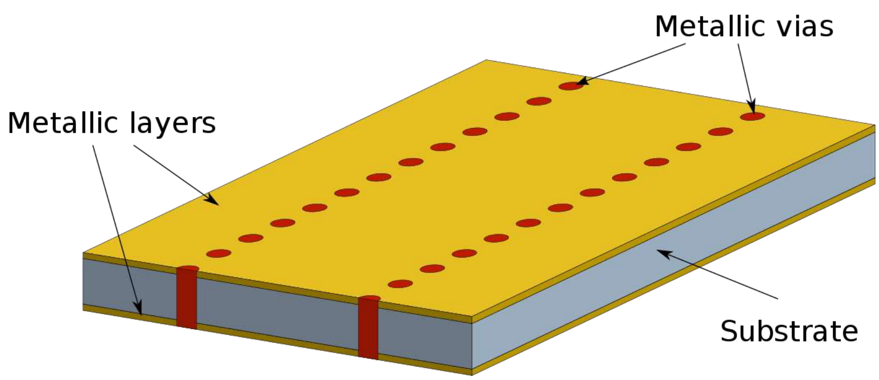

Figure 2.21: SIW Antenna (Microstrip Technology)

2.10 Performance parameters of Antenna

To understand the performance of any Antenna, there are different fundamental figures-of-merit parameters that need to be understood and analyzed before designing any antenna. In the following subsection are deciding parameters for performance of any antenna.

2.11.1 Radiation Pattern

An antenna radiation pattern or antenna pattern is defined as “a mathematical function or a graphical representation of the radiation properties of the antenna as a function of space coordinates. In most cases, the radiation pattern is determined in the far-field region and is represented as a function of the directional coordinates. Radiation properties include power flux density, radiation intensity, field strength, directivity, phase or polarization." The radiation property of most concern is the two or three-dimensional spatial distribution of radiated energy as a function of the observer's position along a path or surface of constant radius.

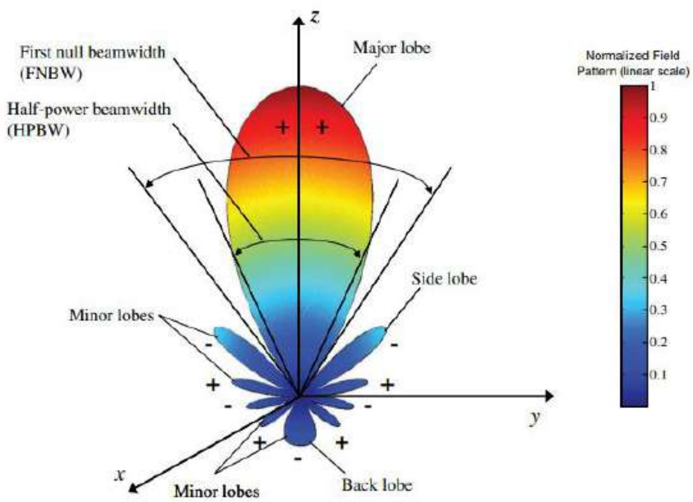

Figure 2.22: Plot of Radiation Pattern of Antenna

An isotropic radiator is defined as "a hypothetical lossless antenna having equal radiation in all directions." Although it is ideal and not physically realizable, it is often taken as a reference for expressing the directive properties of actual antennas. A directional antenna is one "having the property of radiating or receiving electromagnetic waves more effectively in some directions than in others.

2.11.2 Radiation Power Density and Intensity

The Radiation Power density and Intensity relation is vital in case of antennas to understand the transmission of power from guided to free space waves. The equation for the power density shows the relationship between power and energy associated with electromagnetic fields.

$$W = E \times H$$

Where W is Instantaneous Poynting Vector (W/m^2), E is the Electric-Field intensity (V/m) and H is the Magnetic Field intensity (A/m).

Power radiation relation is given by:

$$P_{rad} = P_{av} = \oiint_S W_{rad} \cdot ds$$

Similarly, the Radiation Intensity is given by:

$$U = r^2 W_{rad}$$

Where U is Radiation intensity $(W/\,unit\ solid\ angle)$, W_{rad} is the Radiation density (W/m^2).

2.11.3 Directivity

The directivity of an antenna defined as “the ratio of the radiation intensity in a given direction from the antenna to the radiation intensity averaged over all directions. In mathematical form it can be written as shown below.

$$D = \frac{U}{U_0} = \frac{4\pi U}{P_{rad}}$$

Where D is the directivity (dimensionless), U is the radiation intensity, and P_{rad} is the Power radiated.

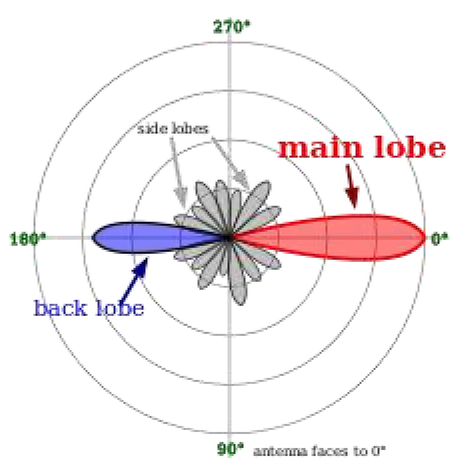

Figure 2.23: Directivity plot of Antenna

2.11.4 Antenna Efficiency

Antenna efficiency is a measure of how effectively an antenna converts input power into radiated electromagnetic waves. It represents the ratio of the power radiated by the antenna to the input power supplied to it. The antenna efficiency includes a lot of parameters along with it, that includes impedance matching (e_r) (or mismatching constant), conduction efficiency (e_c) and dielectric efficiency (e_d).

$$e_0 = e_r e_c e_d$$

Where, e_0 is the overall efficiency.

2.11.5 Gain

Gain of an antenna (in given direction) is defined as "the ratio of the intensity, in a given direction, to the radiation intensity that would be obtained if the power accepted by the antenna were radiated isotopically. It is another useful figure-of-merit describing the performance of an antenna. Although the gain of the antenna is closely related to the directivity, it is a measure that considers the efficiency of the antenna as well as its directional capabilities.

$$Gain = 4\pi \times \frac{Radiation\ Intensity}{Total\ Input\ (accepted) Power}$$

2.11.6 Bandwidth

The bandwidth of an antenna is defined as "the range of frequencies within which the performance of the antenna, with respect to some characteristic, conforms to a specified standard." The bandwidth can be the range of frequencies, on either side of a center frequency (usually the resonance frequency for a dipole), where the antenna characteristics (such as input impedance, pattern, beamwidth, polarization, side lobe level, gain, beam direction, radiation efficiency) are within an acceptable value of those at the center frequency.

2.11.7 Polarization

Polarization of a radiated wave is defined as “that property of an electromagnetic wave describing the time-varying direction and relative magnitude of the electric-field vector; specifically, the figure traced as a function of time by the extremity of the vector at a fixed location in space, and the sense in which it is traced, as observed along the direction of propagation.”

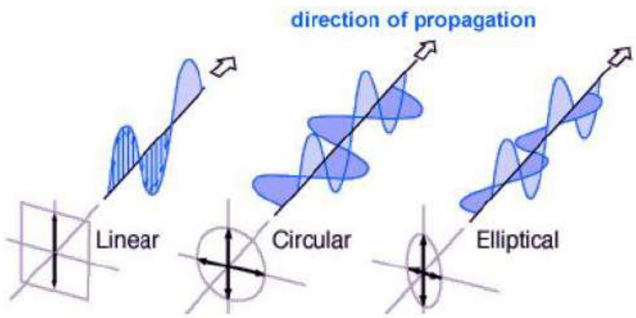

Figure 2.24: Different types of Polarization

2.11.8 Input Impedance

Input impedance is defined as “the impedance presented by an antenna at its terminals or the ratio of the voltage to current at a pair of terminals or the ratio of the appropriate components of the electric to magnetic fields at a point.” In this project the matching part is very significant in terms of antenna efficiency and overall efficiency of the system. The equivalent circuit of an antenna is shown.

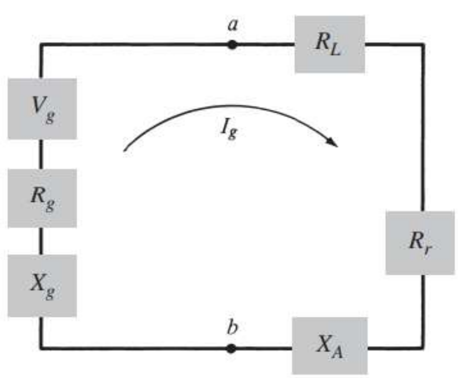

Figure 2.25: Thevenin equivalent circuit of an antenna.

Where,

- V_g is Generator voltage.
- R_g is resistance of generator impedance.
- X_g is reactance of generator impedance.
- R_L is loss resistance of antenna.
- R_r is radiation resistance of antenna.
- X_a is reactance of impedance of antenna.

2.11 Active Antenna with Power Amplifier

In recent years, there have been multiple solutions towards Active Antenna integrated with Power Amplifiers. The figure and circuit below show an example of how integration of antennas with power amplifiers is designed. Hasegawa and Shinohara [reference] explained how GaN HEMT is utilized in Power Amplifier along with Antenna on same substrate.

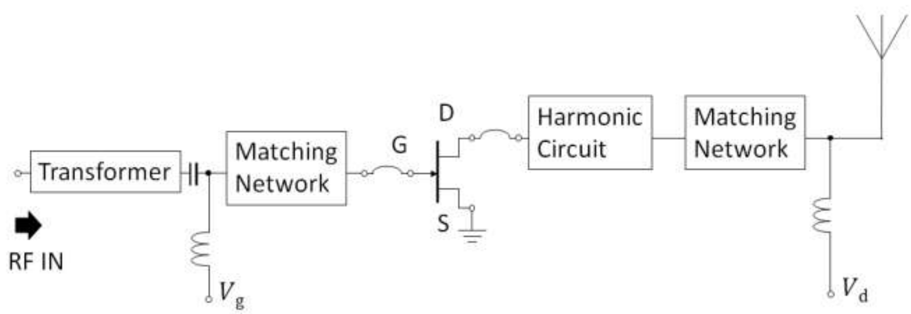

Figure 2.26: Circuit of Active Antenna (PA)

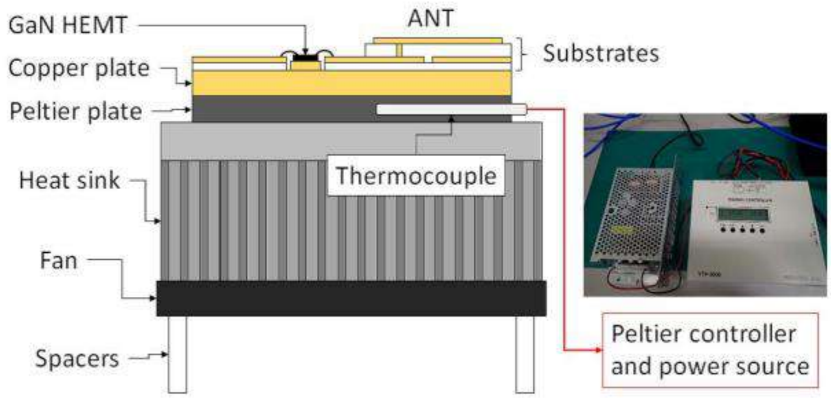

Figure 2.27: Setup for PA with Active Antenna

2.12 Literature Review

References	Class	Gain (dB)	Bandwidth (GHz)	Output Power (W)	Efficiency (%)	Operating Voltage	Antenna	Antenna Properties
[1]	A	10	Ka-Band (30 GHz)	---	15%	28V	Microstrip Loop Antenna	Efficiency 26%
[2]	AB	8	7.10-7.25	30.3dBm	42%	18V	Microstrip Circular Sector	Basic Radiating observed
[3]	AB	---	0.35-3.55	41.9–44.3 dBm	55%	28V	---	---
[4]	E	---	1.78-2.21	22.3 dBm	50%	3V	Microstrip Circular Patch	Circularly Polarized Axial Ratio (<3dB) (1.99-2.18 GHz)
[5]	AB	---	C-band (5-6 Ghz)	37.95 dBm (6.24 W)	62.94%	50 V	Microstrip Array	Gain 23.99 dBi at 5.8 GHz
[6]	--	--	2.04 − 3.29 (S-band)	---	---	---	Quasi-Yagi	Gain (4.86 dBi) at 2.16 GHz

2.13.1 Reference [1]

This paper is based on the initial design flow of a Ka-band Active Integrated Antenna for 5G applications. The objective was to synthesize an antenna impedance that directly matches the amplifier optimal load impedance. Utilizing a Qorvo TGF2942 GaN HEMT, class A Power Amplifier was designed to operate on 28V and was tested with having PAE of 15% at 30 GHz and gain of 10dB. The AIA was a small loop antenna (microstrip technology) for the radiation at desired frequency.

2.13.2 Reference [2]

This paper is based on the design of AIA with PA, for the frequency of 7.25 GHz. The paper mentions the utilization of custom AlGaN HFET for design of PA having linear gain of 8dB and PAE of 42%. The Antenna was tested with measuring the basic radiation at the center frequency.

2.13.3 Reference [3]

This paper is based on the Design of a Compact GaN Power Amplifier with High Efficiency and Beyond Decade Bandwidth. The PA uses GaN HEMT (CG2H40025F) as the transistor and using the ADS simulations and testing it was concluded that the PA achieves an output power of 41.9-44.3 dBm and PAE of 55-74% using range of operating voltages and got the utmost significant bandwidth of 0.35-3.55 GHz (decade).

2.13.4 Reference [4]

This paper is based on Broadband High-Efficiency Linearly and Circularly Polarized Active Integrated Antennas. This paper mentions the utilization of a Class E PA (ATF34143 pHEMT) integrated with linear and circularly polarized designed antennas. This paper more focuses on the AIA part rather than PA. The LP AIA had over 50% PAE with bandwidth of 1.78-2.08 GHz and CP AIA had PAE of >50% with bandwidth of 1.92-2.21 GHz.

2.13.5 Reference [5]

This paper is based on C-Band Active-Antenna Design for Effective Integration with a GaN Amplifier. This paper includes the GaN HEMT SG0601C (Sumitomo Electric) as the transistor for Power Amplifier. The PA came out to have a single-stage PAE of 62.94% with maximum output power of 37.95dBm. A GaN AIA was designed and fabricated on microstrip having maximum antenna gain of 23.99dBi at 5 GHz.

2.13.6 Reference [6]

This paper is based on the Design of an S-Band Transmit-Mode Active Integrated Antenna for Low Power IoT Application. This paper focuses on the design of an AIA operating in S-band. Proposed design utilizes HBT (Heterojunction Bipolar Transistor) for the integration of a Quasi-yagi antenna fabricated on FR4 substrate. The antenna operates on frequency band of 2.04-3.29 GHz, with gain of 4.86dBi. The Antenna had broadside radiation characteristics.

2.13 Applications of Integrated Antenna with Power Amplifier

Some of the major applications of Active Integrated Antenna with Power Amplifier is given below:

- 5G Mobile networks and communications
- Wireless communication devices
- Internet of Things (IoT)
- Satellite communications
- Integration with multiple electronic devices like VR (virtual reality) or AR (Augmented reality)
- Telemedicine and Remote controlling

2.14 Advantages

- A great research prospect with complexity and concepts.

- High frequency response because the active device is ON.
- Targeted for 5G communications which is the most utilized communication protocol and would be used until 6G's hardware matures enough.
- Provides consistent performance across its operating frequency.
- Reduces the use of excess resources as PA with Antenna is more effective and efficient.

2.15 Disadvantages

- Power Amplifiers produce heat during operation.
- They require cooling agents or heat sinks.
- Power Amplifiers may be bulky as heat sink is attached.
- Expensive technology as Transistors (for power amplification) is used.
- Complexity involved in designing.
- Prototype testing is not easy to conduct.

2.16 Software Used

The software that will be used for the completion of this project is Advanced Design System (ADS). It is an electronic design automation software which is produced by Path-Wave Design, which is a division of Keysight Technologies. An integrated design environment is provided to RF electronic product designers by Advanced Design System (ADS).

Keysight Advanced Design System

Figure 2.28: Advanced Design System

For the Antenna designing purposes, CST Studio Suite would be utilized. It is an Electromagnetic Field Simulation Software designed by SIMULIA Software division of Dassault Systems.

Figure 2.29: Computer Simulation Technology (CST) Studio Suite

Chapter 3
Methodology

3.1 Project Approach

A detailed literature review of Power Amplifiers for 5G bands will be carried out along with Antenna theory. Learning of software would be practiced along with trials of different techniques used in the RF field. Design and simulation of the Power amplifier will be carried out and then Active Antenna would be designed followed by the integration of both systems. The software used for the Power Amplifier (PA) design will be ADS 2019. The design of the Antenna would be done on CST Software and final integration on ADS. Design simulations and fabrication would be then carried out followed by comprehensive testing of the prototype will be done to compare results with the results of the simulation.

3.2 Design Specifications

The design specifications for the project are:

- Frequency Range: 3.3 GHz – 4.2 GHz (n77 band (5G))
- Saturated Output Power: 10 W
- Max Input Power: 0 dBm (1mW)
- RF Input Signal Format: CW (Continuous Wave)
- Transistor (FET): GaN HEMT (CGH40010)
- Substrate (dielectric): Rogers 4003C ($\epsilon_r = 3.55$)

3.3 Design Methodology

- Literature Review and understanding of the project.
- Review of concepts for power amplifier and antenna design
- Finalization of an appropriate design model
- Biasing
- Stability Analysis
- Load Pull and Source Pull simulations.
- Input/output impedance matching
- Simulation analysis
- Design of antenna for given frequency
- Optimization of antenna with gain, directivity, and radiation patterns.
- Integration of Power Amplifier with Antenna
- Impedance matching of Antenna.
- Simulation Analysis and Design optimization
- Fabrication and Testing

3.4 Expected Deliverables

The expected deliverables of the project are:

- Design of 10-watts Power Amplifier with integrated Active Antenna for n77 band (5G)
- Prototype Development
- Testing the fabricated prototype

3.5 Resources Required

The resources required for the project are shown in the Table 3.1

Table 3.1: List of resources required.

REQUIREMENTS	STATUS
Vector Network Analyzer	Available
Advanced Design System (Software)	Available
CST Design Studio (Software)	Available

High Processing Workstation	Available
SMA Connectors	To be Procured
GaN HEMT (CGH40010)	To be Procured
Dielectric Substrate	To be Procured
Fabrication Facility	Available
Testing Facility	To be Procured

3.6 Milestones and Time division

Table 3.2: 7th Semester Tasks

TASKS IN 7TH SEMESTER	DURATION
Collecting relevant Data for the project	
Understanding of the project	
Literature Review	
PDD Design	
Survey Report	
Simulations of Power Amplifier	
End Semester Exam Presentation	

Table 3.3: 8th Semester Tasks

TASKS IN 8TH SEMESTER	DURATION
Complete design of Power Amplifier	
Design of Active Antenna	
Integration of Power Amplifier with Active Antenna	
Simulation of complete design	
Mid Term Presentation	
Fabrication of prototype	

Testing, Validation of designed Power Amplifier	
Project Documentation	
End Term Project Presentation	

References

[1] W. -C. Liao et al., "A Ka-Band Active Integrated Antenna for 5G Applications: Initial Design Flow," 2018 2nd URSI Atlantic Radio Science Meeting (AT-RASC), Gran Canaria, Spain, 2018, pp. 1-4, doi: 10.23919/URSI-AT-RASC.2018.8471330.

[2] Younkyu Chung et al., "AlGaN/GaN HFET power amplifier integrated with microstrip antenna for RF front-end applications," in IEEE Transactions on Microwave Theory and Techniques, vol. 51, no. 2, pp. 653-659, Feb. 2003, doi: 10.1109/TMTT.2002.807685.

[3] H. Zhou, J. -R. Perez-Cisneros, B. Langborn, T. Eriksson and C. Fager, "Design of a Compact GaN Power Amplifier With High Efficiency and Beyond Decade Bandwidth," in IEEE Microwave and Wireless Components Letters, vol. 32, no. 12, pp. 1439-1442, Dec. 2022, doi: 10.1109/LMWC.2022.3186805.

[4] Yi Qin, S. Gao and A. Sambell, "Broadband high-efficiency linearly and circularly polarized active integrated antennas," in IEEE Transactions on Microwave Theory and Techniques, vol. 54, no. 6, pp. 2723-2732, June 2006, doi: 10.1109/TMTT.2006.874873.

[5] N. Hasegawa and N. Shinohara, "C-Band Active-Antenna Design for Effective Integration With a GaN Amplifier," in IEEE Transactions on Microwave Theory and Techniques, vol. 65, no. 12, pp. 4976-4983, Dec. 2017, doi: 10.1109/TMTT.2017.2721406.

[6] P. Vangol, A. Mahesh, J. C. Dash and D. Sarkar, "Design of an S-Band Transmit-Mode Active Integrated Antenna for Low Power IoT Application," 2022 IEEE Microwaves, Antennas, and Propagation Conference (MAPCON), Bangalore, India, 2022, pp. 1212-1217, doi: 10.1109/MAPCON56011.2022.10047711.

[7] A. Pal, H. Zhou, A. Mehta, E. Nagasundaram, J. Lees and D. Mirshekar-Syahkal, "Co-design of an antenna-power amplifier RF front-end block without matching network for 2.4 GHz WiFi application," 2017 IEEE Radio and Wireless Symposium (RWS), Phoenix, AZ, USA, 2017, pp. 201-203, doi: 10.1109/RWS.2017.7885987.

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