Kingdom of Saudi Arabia
Imam Muhammad Ibn Saud Islamic University (IMSIU)
Faculty of Science
Department of Mathematics and Statistics

Circular Patch Antenna Design and Simulation

A graduation project submitted to the Department of Physics in partial fulfilment of the requirements for the degree of Bachelor of Science in
Applied Physics

by
Areej Alqaisi
Huda Alsulmi

Supervised by
DR. Asmae Mimouni

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Acknowledgments

بسم الله الرحمن الرحيم

الى أمهاتنا وأباءنا الكرام، فقد كنتم الداعم الأول لِأولى خطواتنا حتى هذه اللحظة المميزة، بكل فخرًا وامتنان نهدي هذا العمل لكم، فقد كنتم الركيزة الأساسية التي استندنا عليها بفضلٍ من الله ثم بفضل توجيهاتكم القيّمة والحكيمة وصبركما وتشجيعكما، تمكنا من تجاوز العقبات والوصول الى الخطوة الأخيرة للخطوة الأولى، أسأل الله أن يمنحكما الصحة والعافية، ويديمكم علينا بكل خيرً وحب وعطاء.

وبحمد الله وشكره، وبعد الله ثم مشرفتنا الكريمة د. أسماء ميموني التي لم تبخل علينا بعلمها الواسع، كانت السبب الرئيسي في انجازنا ما قد يكون أعظم انجاز وليد هذه اللحظة، والنقطة الفاصلة في حياتنا العلمية، فقد كانت جوهرةً بنصائحها ودعمها وتقديرها لنا، والذي أثر علينا في تطوير مهارات لم نكن نعلم اننا قد نكتشفها يومًا ما، تعلمنا منها الدقة والحرص على المحاولة والمثابرة والوصول الى الهدف بدون كللٍ أو ملل، فلها منا جزيل الشكر وخالص التحيات، ونسأل الله أن يجعله في ميزان حسناتها.

إلى إخوتي وأخواتي الأعزاء، الذين كانوا دائمًا السند والداعم النفسي لنا في لحظات التحدي، والذين منحونا القوة والإيجابية للاستمرار حتى النهاية، نقدر كل لحظة دعم وتشجيع قدمتموها لي خلال مسيرتي العلمية.

وأخيرًا أُهدي هذا الإنجاز الى كل من كان له يد في رحلتنا العلمية، أساتذتنا المتميزين دومًا، فضلكم علينا لا يمكن تصوره، فقد كنتم أعظم معلمين لنا، ويجزيكم الله خيرًا على ما تقدمونه لنا وللزميلات، فهو ليس بالسهل، فقد كانت كل لحظة ذات قيمة معهم لِعلمهم العظيم والذي قد يكون سببًا في انجازنا ما هو أعظم في المستقبل.

نسأل الله أن يجعله صالحًا مفيدًا لبني أدم اجمعين.

Abstract

An antenna is a device that transmits and receives electromagnetic waves, and it is essential in all wireless communication systems. It typically consists of three main parts: a radiating patch, a dielectric substrate, and a ground plane. There are many types of antenna, circular patch antenna often made of conductive material ,is placed on top of the substrate, while the ground plane is at the bottom. The substrate separates the two and affects the antenna's performance based on its material properties. In this project, a circular microstrip patch antenna was designed and simulated using CST Studio Suite, a powerful tool for analyzing electromagnetic behavior. To demonstrate the effect of using different dielectric substrates , two different substrate materials, FR-4 and Arlon AD350A, were used in the design of the circular patch antenna fed by a microstrip line. Important antenna characteristics were analyzed,including return loss (S11), VSWR, gain, bandwidth, directivity, efficiency, and radiation pattern. Simulation results showed that Arlon AD350A provided superior performance in terms of return loss, VSWR, gain, and efficiency, making it more suitable for advanced, high-frequency applications.

الملخص

الهوائي هو جهاز يرسل ويتلقى الموجات الكهرومغناطيسية، وهو عنصر أساسي في جميع أنظمة الاتصالات اللاسلكية، يتكون الهوائي عادةً من ثلاثة أجزاء رئيسية: الهوائي المشع، وطبقة عازلة، وطبقة أرضية، توجد العديد من أنواع الهوائيات، وغالبًا ما يتم تصنيع الهوائي الدائري باستخدام مواد موصلة، ويتم وضعه على قمة الطبقة العازلة، بينما تكون الطبقة الأرضية في الأسفل، تفرق الطبقة العازلة بين الهوائي المشع و الأرضية وتؤثر على أداء الهوائي بناءً على خصائص مادتها.

في هذا المشروع، تم تصميم هوائي دائري من النوع المايكروستريب وتم محاكاته باستخدام برنامج CST Studio Suite وهو أداة قوية لتحليل السلوك الكهرومغناطيسي.

لتحليل تأثير استخدام مواد مختلفة للطبقات العازلة على أداء الهوائي، تم استخدام مادتين مختلفتين للطبقات العازلة، وهم FR-4، Arlon AD350A في تصميم الهوائي الدائري الذي يتم تغذيته بواسطة خط مايكروستريب.

تم تحليل الخصائص الرئيسية للهوائي، بما في ذلك معامل الانعكاس(S11) ، نسبة الموجات الموقوفة (VSWR)، والكفاءة، عرض النطاق الترددي، الاتجاهية، ونمط الإشعاع.

أظهرت نتائج المحاكاة أن Arlon AD350A قدم أداءً متفوقًا من حيث معامل الانعكاس، نسبة الموجات الموقوفة، والكفاءة، مما يجعله أكثر ملاءمة للتطبيقات المتقدمة والترددات العالية.

Chapter 1

Patch Antenna theory

1.1 General Introduction

In modern telecommunications systems, there is a growing need for compact and small antennas. In recent years, the microstrip patch antenna has widely been used for various specific applications in satellite communications, aerospace, radars, biomedical applications, both military and commercial applications mobile communication for GSM, and remote sensing applications because of its special features like ease of analysis and fabrication, low cost, light weight, easy to feed, capability of dual, triple and several frequency operations and attractive radiation . Although the patch antenna has several advantages, it has some limitations like narrow bandwidth. The need for wideband antennas operating at higher frequencies is significantly increasing as the various wireless applications require more and more bandwidth. To meet the growing demands of the communication systems, researchers have continuously developed new and effective methods to improve the different features of microstrip patch antennas like bandwidth, polarization, gain , return loss, directivity, etc. However, circular structures have been found to have smaller dimensions related to the operations of the frequency. It is very easy and simple to design and control the radiation patterns in circular patch antennas as compared to the rectangular antenna where the length and width of the patch are used to control and design [1]. There are different types of feeding techniques of a patch antenna like: probe feed, microstrip line feed, aperture coupled feed and proximity coupling feed. This project provides a detailed description about the design and development of a microstrip circular patch antenna fed by a 50Ω microstrip transmission line since it is most commonly used and very easy to design for wireless applications. Chapter 1 presents generality on antennas, their definition, mode of operation, antenna parameters, types of antennas, feeds and especially the microstrip line feed, its advantages and limitations. Chapter 2 aims to design and simulate a circular patch antenna for two material substrates: Arlon AD350A with a dielectric constant of 3.5 and FR-4 with a dielectric constant of 4.3, fed by a microstrip line using CST Microwave Studio software for application in the

5.4 GHz frequency band.[2].

1.2 Microstrip Patch Antenna

1.2.1 Description of a Microstrip Patch Antenna

A microstrip patch antenna is a compact and low-profile radiating structure that is widely utilized in contemporary wireless communication systems. It typically consists of three fundamental layers: a conducting patch on top, an insulating substrate in the middle, and a conductive ground plane at the bottom figure 1.1

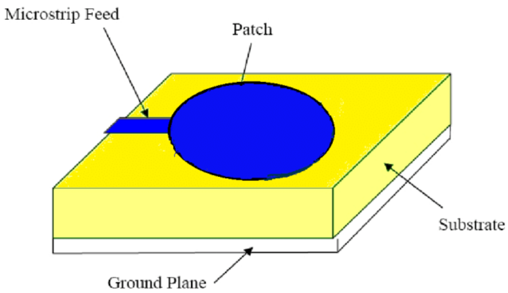


Figure 1.1: Microstrip Patch Antenna

The top metallic patch, which functions as the primary radiating component, is often made of high-conductivity materials such as copper or gold. Its shape can vary, commonly rectangular, circular, triangular, or elliptical, depending on the desired performance characteristics and application requirements. The dielectric substrate plays a critical role in separating the patch from the ground plane and influencing key parameters such as impedance, bandwidth, and resonant frequency. This layer is usually composed of a material with a specific dielectric constant, which must be carefully selected to optimize the performance of the antenna. The ground plane below serves as a reference point and reflects the radiated waves, contributing to the directional behavior of the antenna. Radiation occurs when an alternating signal is applied through a feeding mechanism, causing surface currents to flow in the patch. These currents result in the accumulation of positive and negative charges at the patch edges, leading to the formation of fringing electric fields. These fields are responsible for radiating electromagnetic waves into free space. For optimal performance, the physical length of the patch is generally designed to be around half the wavelength that corresponds to the operating frequency of the antenna [3].

1.2.2 Types of Patch Antennas

The Microstrip patch antennas are available in a diverse array of configurations, typically classified according to the geometry of the radiating patch and the chosen feeding mechanism. Each variation is designed to fulfill specific performance objectives such as enhanced bandwidth, reduced size, controlled polarization, or ease of fabrication. Among the various geometries, figure 1.2

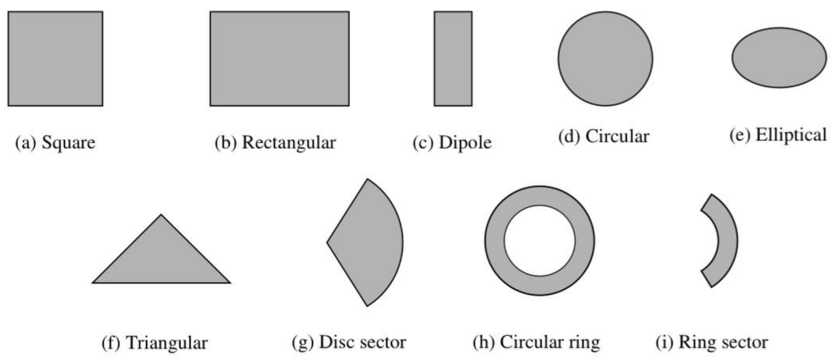


Figure 1.2: Types of Patch Antennas

- **Rectangular Patch** is the most widely used due to its straightforward design and ease of theoretical analysis. It is particularly effective for applications requiring linear polarization and narrow band directional radiation. [3]

- **Circular Patch** is preferred for systems demanding circular polarization, such as satellite communication, and offers a reduced physical footprint at the same resonant frequency, making it suitable for compact layouts. Other specialized shapes also serve unique purposes. [3]

Triangular patches are known for their compactness and compatibility with microstrip lines. [3]

elliptical patches are valued for their larger bandwidth and flexible polarization behavior. [3]

Fractal-shaped patches, with their self-repeating structures, are engineered for multi-band or ultra-wideband applications. Their intricate geometry allows resonance at multiple frequencies, making them ideal for compact, frequency-agile systems. [3]

slot patch antenna, which includes one or more slots carved into the patch, alters the surface current distribution to allow dual-frequency operation or polarization diversity.[3]

1.2.3 Advantages and Disadvantages of Patch Antennas

Microstrip patch antennas have numerous advantages that contribute to their widespread use in modern wireless communication systems. The primary benefit of their low profile and lightweight design is that it allows seamless integration onto both flat and curved surfaces. This makes them particularly suitable for applications in portable electronic devices, aerospace systems, and satellite platforms. Their compatibility with printed circuit board (PCB) fabrication is another key strength, allowing cost-effective mass production and integration with other radio frequency (RF) components on the same substrate - critical for compact and efficient system layouts. These antennas are also highly versatile in terms of design flexibility. By adjusting the patch geometry or incorporating slots, stacked layers, or parasitic elements, designers can achieve dual-band or multi-band performance, meeting the frequency requirements of diverse communication standards. Despite these advantages, microstrip patch antennas are not without drawbacks. One of their most prominent limitations is their inherently narrow bandwidth, which can restrict the operational frequency range. This makes them less ideal for wideband or broadband applications unless they are enhanced through advanced design techniques. Additionally, their radiation efficiency and gain are typically lower compared to other antenna types such as horn or parabolic reflector antennas. Another concern is the excitation of surface waves within the dielectric substrate, particularly when materials with high permittivity are used. These surface waves can lead to energy loss and reduced radiation efficiency. Furthermore, the performance of microstrip antennas is often sensitive to manufacturing tolerances and environmental changes such as temperature fluctuations and humidity, which can cause changes in resonant frequency or impedance mismatch [3].

1.2.4 Operating Principle

The functioning of a microstrip patch antenna is governed by the concept of electromagnetic resonance. When a radio frequency (RF) signal is delivered through the feed line, surface currents are induced on the conductive patch. These currents lead to the accumulation of charges near the patch edges, generating fringing electric fields that extend into the surrounding environment. This fringing effect facilitates the radiation of electromagnetic energy into free space. Maximum radiation efficiency is achieved when the patch's physical length is approximately half the guided wavelength within the dielectric material. Because the wavelength on the substrate is shorter than in free space - due to the influence of the relative permittivity of the material - the antenna must be carefully dimensioned based on the effective dielectric constant of the substrate. The resonant frequency of the antenna is dictated primarily by several key parameters: the shape and size of the radiating patch, the thickness and dielectric constant of the substrate, and the type of feeding mechanism employed. When the antenna is properly designed, it exhibits a broadside radiation pattern, which means the strongest radiation is emitted perpendicular to the plane of the patch. To fine-tune the antenna performance, engineers typically evaluate parameters such as return loss, impedance matching, bandwidth, and radiation characteristics. These are analysed using electromagnetic simulation tools, which allow precise modelling and optimization of the antenna structure to meet specific application requirements [3].

1.2.5 Applications

Microstrip patch antennas are extensively utilized in numerous technological domains due to their compact structure, design flexibility, and ease of integration with planar circuits. In the field of wireless communications, these antennas are commonly incorporated into mobile phones, tablets, laptops, and other portable devices, where their low profile and lightweight characteristics are essential for space-efficient designs. Their ability to provide reliable signal transmission and reception makes them a preferred choice for consumer electronics. In satellite communication, microstrip antennas—particularly those designed for circular polarization—are used to ensure stable signal quality regardless of relative orientation between the satellite and the receiver. They are also critical components in Global Positioning System (GPS) receivers, offering consistent and accurate signal acquisition from satellite constellations. The aerospace and defence sectors leverage the conformal nature of microstrip antennas, allowing them to seamlessly integrate into the surfaces of aircraft, missiles, and armoured vehicles. This not only improves aerodynamic performance but also contributes to low-observable (stealth) designs by reducing the radar cross-section. In the medical field, microstrip patch antennas are increasingly used in wireless body area networks (WBANs) and implantable biomedical devices for real-time patient monitoring. Their compatibility with flexible substrates and biocompatible materials supports their integration into wearable and implantable technologies. The rise of the Internet of Things (IoT) has further expanded the role of microstrip antennas in smart home systems, industrial automation, and environmental monitoring. These antennas enable reliable wireless communication between distributed sensors, actuators, and control units, facilitating efficient data transmission and real-time system responsiveness in complex IoT ecosystems [3].

1.3 Feeding Techniques in Antenna Design

The term feeding techniques refers to the various methods employed to deliver electromagnetic energy from a transmission line to the antenna's radiating element. A fundamental objective of these techniques is to facilitate efficient power transfer while achieving impedance matching between the feed system and the antenna, thereby minimizing reflection and power loss. The selection of an appropriate feeding mechanism significantly influences key antenna performance metrics. Each technique presents distinct trade-offs in complexity, bandwidth, fabrication requirements, and performance, and is therefore chosen based on the specific application and design constraints of the antenna system [4].

1.3.1 Microstrip Line Feed

it's the most commonly employed methods for exciting a microstrip patch antenna. It involves a direct electrical connection between a narrow conductive strip and the edge of the patch antenna. This strip is printed on the top surface of a dielectric substrate, forming a planar transmission line structure capable of guiding high-frequency electromagnetic signals. The performance of the microstrip line feed is significantly influenced by its characteristic impedance, which is governed by the strip's width, the substrate thickness, and the dielectric constant of the material. Accurate impedance matching is essential to reduce signal reflection and optimize power transfer. The major advantages of this technique are its ease of fabrication, as both the radiating patch and the feed line are created on the same substrate using standard printed circuit board (PCB) processes. The microstrip line feed remains a preferred solution for many practical applications, including wireless communication devices, GPS systems, and mobile handsets, due to its simplicity and cost-effectiveness figure 1.3 [3].

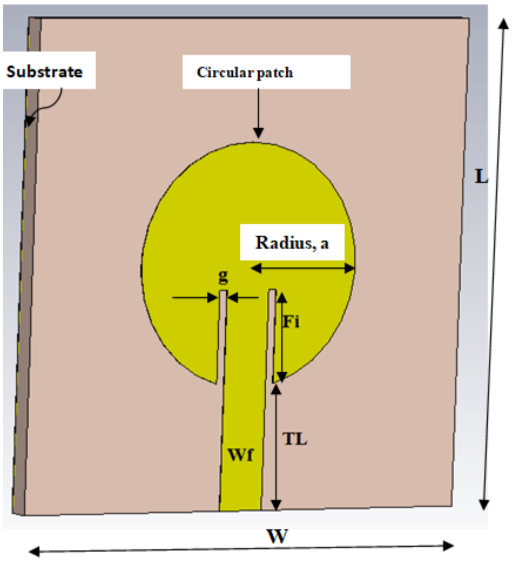


Figure 1.3: Feed Line

1.3.2 Coaxial Probe Feed

The coaxial probe feed represents a widely utilized and adaptable method for exciting microstrip patch antennas, particularly valued for its ability to provide precise control over impedance matching. This approach employs a coaxial cable in which the inner conductor passes through the dielectric substrate and is soldered directly to the radiating patch, while the outer conductor is connected to the ground plane beneath the substrate. A key feature of this technique is the ability to adjust the feed point location on the patch surface, allowing fine-tuning of the input impedance to achieve optimal impedance matching. This adjustability enhances power transfer efficiency and reduces signal reflection, which is particularly beneficial in applications demanding precise control over electromagnetic performance. Despite its advantages, the coaxial probe feed does introduce certain fabrication complexities. Nonetheless, the method remains a favored solution in a range of high-performance applications, including satellite communications, radar systems, and advanced wireless networks, due to its design flexibility and support for a broad frequency spectrum [3].

1.3.3 Slot Coupling Feed

The slot-coupling feed represents a more sophisticated approach in microstrip antenna design, where energy is transferred through a narrow slot or aperture etched in the ground plane. In this configuration, the feed line is placed beneath the ground plane, while the radiating patch resides above it. Electromagnetic energy is coupled from the feed line to the patch through the slot, enabling effective excitation without requiring a direct electrical connection. The size, shape, and position of the slot are critical factors influencing the antenna's performance, particularly its impedance characteristics and bandwidth. One of the primary advantages of this method is the enhanced isolation it offers between the feed network and the radiating element, significantly reducing spurious radiation and mutual coupling. Compared to traditional feeding techniques, such as the microstrip line feed, slot coupling generally supports a wider bandwidth, making it highly desirable for applications where frequency agility is essential [3].

1.3.4 Proximity coupling power supply

Proximity coupling is an indirect feeding mechanism employed in microstrip antenna systems, where power is transmitted via electromagnetic coupling rather than through a physical connection. In this configuration, the feed line is positioned on a separate substrate layer beneath the radiating patch, with a dielectric layer in between, allowing energy to be transferred through electromagnetic fields across the dielectric interface. This method relies on magnetic or resonant inductive coupling, where a magnetic field formed between closely spaced structures facilitates energy exchange. The spatial alignment of the feed line and patch, along with the operating frequency, plays a significant role in determining the efficiency of the energy transfer. Optimal performance is typically observed when the system is tuned to its resonant frequency, minimizing reflection losses and enhancing power delivery. Key design parameters such as resonator geometry, inter-element spacing, and substrate characteristics must be carefully engineered to achieve effective coupling. Proximity-coupled feeds are widely used in advanced applications where non-contact energy transmission is required, such as wireless charging systems, implantable medical devices, and short-range communication modules [3].

1.4 Microstrip Patch Antenna Characteristics

1.4.1 Return Loss (S11)

The return loss is a fundamental parameter that reflects how effectively power is delivered from a transmission line to an antenna. It is a measure of the mismatch between the antenna and the feed line, indicating the amount of power that is reflected back toward the source rather than being radiated by the antenna. This parameter is typically expressed in decibels (dB), and a more negative return loss value signifies better impedance matching and thus more efficient power transfer. Return loss is directly related to the reflection coefficient, often denoted as S11 in the context of scattering parameters used in high-frequency circuit analysis. The term S11 represents the input port reflection coefficient in a two-port network, where the port under consideration is both the input and the output. From a theoretical perspective, the reflection coefficient is derived from the ratio of the reflected voltage wave to the incident voltage wave at the antenna input. If the impedance of the antenna perfectly matches the characteristic impedance of the feed line, which is commonly 50 ohms, the reflection coefficient becomes zero and the return loss approaches negative infinity, signifying an ideal match. Designers aim for return loss values better than -10 dB across the intended operating frequency band, which corresponds to a reflection coefficient magnitude of approximately 0.316 and indicates that at least 90 percent of the input power is delivered to the antenna [3].

1.4.2 Input Impedance of Microstrip Patch Antennas

The input impedance of a microstrip patch antenna is a key factor that determines how effectively power is transferred from the feed line to the antenna. Proper impedance matching is essential to minimize signal reflection and maximize radiation efficiency. This impedance is influenced by several parameters, including the patch dimensions, substrate material, feed method, and operating frequency. In rectangular patch antennas, the impedance varies along the patch surface, being lower at the edges and higher toward the center. By choosing the right feed point, designers can match the antenna's impedance to standard transmission lines, typically 50 ohms. The substrate's dielectric constant and thickness also play a role, as they affect the distribution of electromagnetic fields and the level of fringing at the patch edges. A higher dielectric constant tends to lower the impedance, while a thicker substrate can increase it. Different feeding techniques offer varying levels of control over the input impedance. Simpler methods like microstrip line or coaxial feed are easy to implement and allow basic impedance adjustments [3].

1.4.3 Radiation Pattern of Microstrip Patch Antennas

The spatial distribution of the radiated power as a function of direction. It is a fundamental characteristic that reflects the ability of the antenna to direct energy in desired directions while minimizing radiation in undesired ones. Typically, microstrip patch antennas exhibit a broad-side radiation pattern, which means that the maximum radiation occurs perpendicular to the surface of the patch. This pattern is generally symmetric and resembles a dumbbell shape in the E-plane, offering a directive beam with moderate gain. The shape and behavior of the radiation pattern are influenced by several design parameters, including the dimensions of the patch, the substrate properties, and the operating frequency. The width and length of the patch determine the resonant modes, which in turn shape the pattern. In the fundamental mode, the antenna radiates primarily in the broadside direction, while higher-order modes may introduce additional lobes or alter the pattern symmetry. A higher dielectric constant tends to concentrate the fields within the substrate, which can slightly narrow the beam width and reduce back radiation. However, because of their low profile and planar nature, microstrip antennas often suffer from limited bandwidth and lower efficiency compared to other antenna types, which may slightly distort the ideal pattern. Despite these limitations, the microstrip patch antenna remains highly desirable for many modern applications due to its predictable radiation behaviour, ease of integration, and suitability for array configurations [3].

1.4.4 Gain and Directivity

In antenna theory, the concepts of gain and directivity are fundamental to understanding how efficiently an antenna radiates energy in a specific direction. Both parameters are measures of the antenna's ability to focus radiated power, yet they differ in the aspects they emphasize. Directivity is a measure that indicates how concentrated the radiation is in a particular direction, without taking into account any losses due to the antenna's physical construction or imperfections. It is defined as the ratio of the radiation intensity in a given direction to the average radiation intensity over all directions. Essentially, it reflects the directional properties of the antenna's radiation pattern and serves as a purely geometric property of the antenna. A high directivity implies that the antenna radiates more energy in a particular direction rather than dispersing it uniformly in all directions. On the other hand, gain encompasses both the directivity of the antenna and its efficiency. It provides a more realistic representation of the antenna's performance by accounting for power losses that occur due to conduction, dielectric, and other losses in the antenna structure. Gain is defined as the ratio of the radiation intensity in a specific direction to the radiation intensity that would be obtained if the input power were radiated isotropically. This makes gain a practical figure of merit, as it reflects not only the antenna's directional capability but also how effectively it converts input power into radiated electromagnetic energy. While gain and directivity may have similar numerical values for highly efficient antennas, gain will always be less than or equal to directivity due to the inclusion of efficiency. The mathematical expression for directivity is derived from the radiation intensity function and normalized with respect to the average radiation intensity. In contrast, the gain is typically expressed in terms of decibels relative to an isotropic radiator (dBi), and it is calculated by multiplying the directivity by the antenna efficiency. In real-world applications such as satellite communication, radar systems, and wireless networks, both gain and directivity are critical factors that influence the range, reliability, and clarity of the transmitted signals. Thus, gain and directivity are not only theoretical measures but also practical indicators of antenna effectiveness [3].

1.4.5 Standing Wave Ratio

The standing wave ratio is a critical parameter in the analysis and performance evaluation of transmission lines and antennas. It arises from the phenomenon of wave reflection caused by impedance mismatches along the transmission path. When an incident wave traveling along a transmission line reaches a point where the load impedance does not match the characteristic impedance of the line, a portion of the wave reflects back toward the source. The interaction between the incident and reflected waves produces a standing wave pattern, characterized by points of maximum and minimum voltage along the line. SWR is defined as the ratio of the amplitude of the maximum voltage to the amplitude of the minimum voltage in the standing wave. This ratio is always greater than or equal to one, with a value of one indicating perfect impedance matching and thus the absence of any reflected wave. As the mismatch increases, so does the SWR, signifying greater power reflection and reduced transmission efficiency. A high SWR indicates poor matching conditions, which can lead to significant power losses and even damage to the transmitter in severe cases. In antenna systems, maintaining a low SWR is essential for ensuring efficient power transfer from the transmission line to the antenna and ultimately into free space. The SWR is directly related to the reflection coefficient, and both are used interchangeably in system analysis to assess the quality of impedance matching [3].

1.4.6 Bandwidth

Bandwidth is a fundamental parameter in antenna theory that characterizes the range of frequencies over which an antenna operates effectively. It represents the range of frequencies within which the antenna maintains satisfactory performance in terms of radiation efficiency, impedance matching, and gain. An antenna does not radiate efficiently across all frequencies; rather, its performance is optimized within a specific frequency range, and this range is defined as its bandwidth. The bandwidth of an antenna is typically expressed as a percentage of the center frequency or in absolute terms such as megahertz or gigahertz. Antenna bandwidth depends on several factors including the antenna's geometry, type, size, and the dielectric properties of the surrounding materials. For instance, wide band antennas such as log-periodic or spiral antennas are specifically designed to operate over a large frequency range, while narrowband antennas such as patch antennas are limited to a smaller bandwidth unless special techniques are applied. In practical applications, bandwidth is a key consideration when selecting or designing antennas for communication systems, radar, satellite links, and broadcasting [3].

1.4.7 Polarization

Polarization is a key characteristic of electromagnetic waves that describes the orientation of the electric field vector as the wave propagates through space. In antenna theory, polarization plays a crucial role in determining how effectively an antenna can transmit or receive energy. The polarization of the wave must align with that of the receiving antenna to ensure maximum power transfer. Depending on the behavior of the electric field vector over time, polarization can take various forms, including linear, circular, or elliptical. A clear understanding of polarization is essential for designing efficient communication systems and selecting appropriate antennas for specific applications [3].

1.4.7.1 Linear Polarization

Polarization is a key characteristic of electromagnetic waves that describes the orientation of the electric field vector as the wave propagates through space. In antenna theory, polarization plays a crucial role in determining how effectively an antenna can transmit or receive energy. The polarization of the wave must align with that of the receiving antenna to ensure maximum power transfer. Depending on the behavior of the electric field vector over time, polarization can take various forms, including linear, circular, or elliptical. A clear understanding of polarization is essential for designing efficient communication systems and selecting appropriate antennas for specific applications [3].

1.4.7.2 Circular Polarization

Linear polarization refers to a condition in which the electric field vector of an electromagnetic wave maintains a constant direction as the wave propagates through space. This means that at every point along the direction of propagation, the electric field oscillates within a single plane. The orientation of this field defines the specific type of linear polarization, which is typically categorized as either vertical or horizontal. In vertically polarized waves, the electric field oscillates in a vertical plane, while in horizontally polarized waves, it oscillates in a horizontal plane. The linear polarization can also be oriented at any arbitrary angle, depending on the orientation of the antenna. In antenna design, linear polarization is one of the most commonly used forms due to its simplicity and ease of implementation. Antennas such as dipoles, monopoles, and many microstrip patches are naturally linearly polarized, radiating energy in a fixed polarization plane. Understanding linear polarization is essential for antenna engineers and system designers, as it directly impacts link performance, radiation characteristics, and polarization compatibility between system components [3].

Chapter 2

Design Simulation

2.1 Introduction

In recent years, microstrip patch antennas have become increasingly popular in various specialized fields such as satellite communications, aerospace, radar systems, biomedical applications, GSM mobile communication, and remote sensing. This widespread usage is primarily due to their unique advantages, including ease of design and fabrication, low cost, lightweight structure, and the ability to support multiple frequency bands. Despite these benefits, microstrip patch antennas face limitations, such as narrow bandwidth. As the demand for high-frequency applications continues to grow, so does the requirement for broader bandwidth and better performance. In this chapter, it has been designed using CST microwave studio software and displays the parameters by the figures. First of all, there is a need to choose the dielectric constant and substrate height, and these are the basics to design an antenna. These are chosen according to the design frequency, and our designed frequency is 5.4 GHz [2].

2.2 CST Program

CST Studio Suite, developed by Dassault Systèmes, is a comprehensive software package used for the simulation of electromagnetic (EM) fields in 3D. It is widely applied in the design and analysis of components operating across the electromagnetic spectrum, including antennas, filters, connectors, PCBs, and microwave circuits. CST utilizes several high-performance numerical solvers such as the Time Domain Solver, Frequency Domain Solver, and Eigenmode Solver, which allow accurate modeling of both static and dynamic EM behavior in complex structures.One of the key strengths of CST Studio Suite lies in its ability to perform full-wave electromagnetic simulation, enabling users to predict and optimize device performance without physical prototypes. It also supports co-simulation with other tools (e.g., thermal and mechanical simulators), making it highly suitable for multiphysics applications. The software's intuitive GUI, parametric modeling features, and powerful post-processing tools make it a preferred choice for engineers and researchers in fields like RF/microwave engineering, wireless communication, aerospace, defense, and biomedical applications [5]

2.3 Theoretical Calculation

2.3.1 Determination of the dimensions of the circular patch antenna:

The antenna consists of 3 layers of substrate. Top view layer 1 is a patch and microstrip line. A patch is a radiator element, so it is located at the very top. This element serves to radiate electromagnetic wave energy into free space and receive electromagnetic waves from free space. The type of patch used is a circular patch. Conductor strips are inserted between layer 2 and 3 substrates and between layer 1 and 2. This conductor strip will serve to increase the permittivity of the dielectric material. The lowest layer is the ground plane. This ground plane serves to terminate the electrons coming from the patch [6].

To design a circular microstrip patch antenna, the essential parameters are [2]:

- **The operating frequency f0 = 5.4 GHz.**
- **Dielectric constant of substrate $\varepsilon_{\mathbf{r}}$.**

Calculation of effective dielectric constant ($\varepsilon_{\mathbf{reff}}$):

$$\varepsilon_{\text{reff}} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left[1 + 12\frac{h}{W}\right]^{-\frac{1}{2}} \tag{2.1}$$

- **The radius of the circular patch antenna**

The radius of the circular patch is calculated by using the following equation

$$a = \frac{F}{\left\{1 + \frac{2h}{\pi\varepsilon_r F}\left[\ln\left(\frac{\pi F}{2h}\right) + 1.7726\right]\right\}^{\frac{1}{2}}} \tag{2.2}$$

$$where, F = \frac{8.791 \times 10^9}{f_r\sqrt{\varepsilon_r}} \tag{2.3}$$

- **The length and width of the substrate plane WS and LS.**

The length and width of the substrate are normally taken as two times the diameter of the circular patch.

L = 2 × Patch Diameter = 2 × (2a)
W = 2 × Patch Diameter = 2 × (2a)

- **Substrate height (h)= 1.6**
- **Conductor thickness (t)=0.035**
- **determination of the dimensions of the microstrip feed line:**

There are different types of feeding techniques of a patch antenna. The proposed antenna is fed by a 50Ω microstrip transmission line. The fed is inserted into the circular radiating element for proper impedance matching. The fed parameters are:

- **Microstrip transmission line length:**

TL=2a

- **Inset feed length (Fi):**

$$Fi = \frac{\cos^{-1}\left(\sqrt{\frac{Z_0}{R_{in}}}\right)}{\sqrt{\frac{\pi}{L}}} \tag{2.4}$$

Where the resonance input impedance is calculated by the equation:

$$R_{in} = \frac{1}{2(G_1 + G_{12})} \tag{2.5}$$

The inset feed introduces a physical notch, which in turn introduces a junction capacitance. The junction capacitance G1 and G12 can be calculated using the following equations:

$$G_1 = \frac{l_1}{120\pi^2} \tag{2.6}$$

$$where, I_1 = \int_0^{\pi} \left[\frac{\sin\left(\frac{k_0 W}{2}\cos\theta\right)}{\cos\theta}\right]^2 d\theta \tag{2.7}$$

$$k_0 = \frac{2\pi}{\lambda} \tag{2.8}$$

And G12 is calculated as

$$G_{12} = \frac{1}{120\pi^2}\int_0^{\pi} \left[\frac{\sin\left(\frac{k_0 W}{2\cos\theta}\right)}{\cos\theta}\right]^2 J_0(k_0 L \sin\theta)\sin^3\theta \, d\theta \tag{2.9}$$

- **Microstrip feed line width (Wf)**

To obtain 50Ω characteristic impedance (Z0), the required feed line width to height ratio (Wf/2) can be calculated using the formula:

$$\frac{Wf}{2} = \left\{\frac{2}{\pi}\left(B - 1 - \ln(2B-1) + \frac{\varepsilon_r - 1}{2\varepsilon_r}\left[\ln(B-1) + 0.39 - \frac{0.61}{\varepsilon_r}\right]\right)\right.$$

$$\text{when } \frac{Wf}{2} \geq 2$$

$$where, A = \frac{Z_0}{60}\sqrt{\frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r + 1}{\varepsilon_r - 1}\left(0.23 + \frac{0.11}{\varepsilon_r}\right)}$$

$$andB = \frac{377\pi}{2Z_0\sqrt{\varepsilon_r}}$$

we introduce the characteristics of the patch antenna and the microstrip feed line in CST Studio Program.

The basic structure of an inset feed circular patch antenna is shown in figure 1.1

2.3.2 Performance Analysis

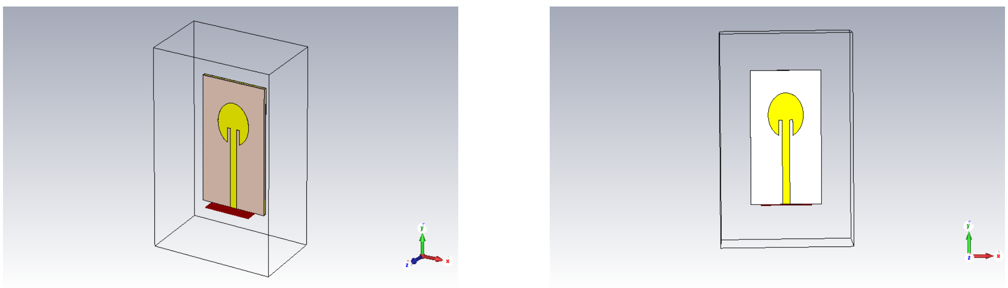
In this study, an inset-fed circular microstrip patch antenna is designed and simulated using CST Microwave Studio, employing various dielectric substrate materials. The antenna was designed using Arlon AD 350 with a dielectric constant of 3.5 and FR-4 with a dielectric constant of 4.3. The dimensions of the proposed antenna for Arlon AD 350 and FR-4 dielectric material are shown in table 2.1

Table 2.1: Patch antenna design parameters Arlon AD 350 Dielectric Material for $\varepsilon_r = 3.5$ and FR-4 Dielectric Material for $\epsilon_r = 4.3$

Description	Dimensions(mm)	
Material	Alron AD 350	FR-3
Patch radius	8.8656	8.0523
Substrate length (Lg)	35.4624	32.2092
Substrate width (W)	35.4624	32.2092
Inset feed length (Fi)	6.7822	6.2782
microstrip transmission line length	17.7312	16.1046
Dielectric constant of substrate	3.5	4.3
Microstrip feed line width (wf)	3.31	3.323
Substrate height (h)	1.6	
Conductor thickness (t)	0.035	

2.4 Design Simulation

An inset line feed circular microstrip patch antenna using different dielectric substrates is designed and simulated using CST program [5].



(a) First (b) Second

Figure 2.1: Front and Side View of the Design

Chapter 3

Results and Discussion

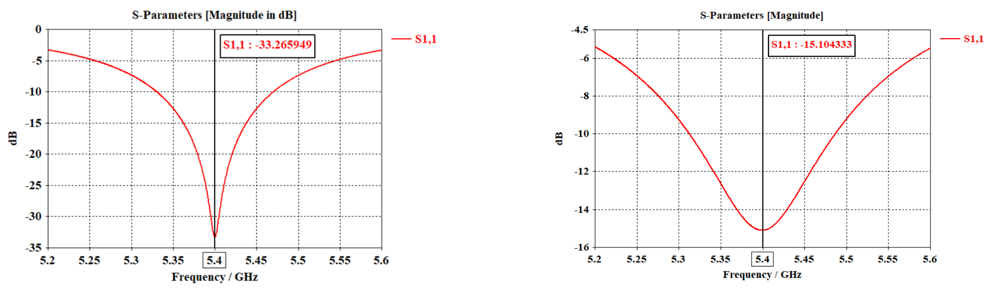
3.1 Simulation results:

The CST software used to simulate the antenna design can display several antenna parameters such as return loss (S11), VSWR, gain, directivity, radiation pattern, and efficiency. To analyse and evaluate the antenna performance of the proposed antenna design using these antenna parameters, the summary of the results of the simulated antenna designs for the designed circular patch antenna is presented and discussed below [5]

3.1.1 Return Loss (S11):

Return loss is an important parameter that measures the effective power delivery of the designed antenna .

The figure 2.1(a,b) plots the return loss or reflection response (S11) of the designed circular patch antenna.



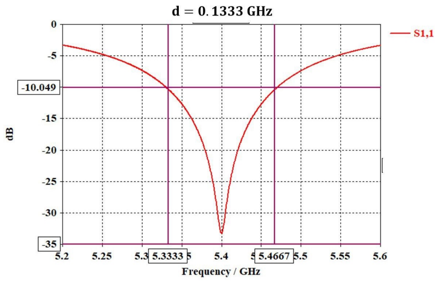
(a) First (b) Second

Figure 3.1: (a) Return Loss vs. frequency plot of designed circular patch antenna dielectric material of Arlon AD 350. (b) Return Loss vs. frequency plot of designed circular patch antenna dielectric material of FR-4.

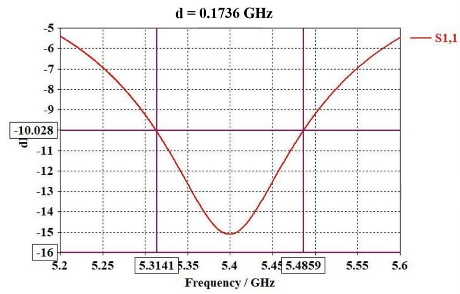
It is evident that the designed circular patch antenna is resonating at the operating frequency of 5.4 GHz, with a measured return loss of -33.26 dB for Arlon AD 350 and -15.10 dB for FR-4.

3.1.2 Bandwidth:

To see where the antenna is going to work ”bandwidth,” we are going to find the representation in dB of the frequency band corresponding to S11 ¡ -10.



(a) First



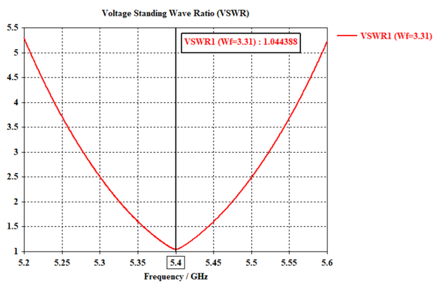
(b) Second

Figure 3.2: (a) Bandwidth of designed circular patch antenna dielectric material of Arlon AD 350. (b) Bandwidth of designed circular patch antenna dielectric material of FR-4.

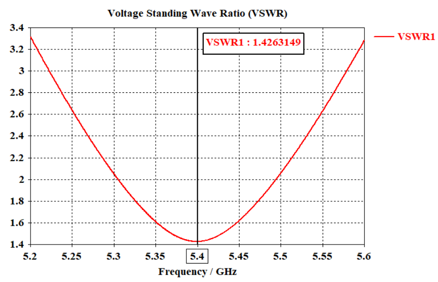
The bandwidth figure 2.2(a,b) for the circular patch antenna for Arlon AD 350 dielectric is 0.1333 GHz and for FR-4 dielectric is 0.1736 GHz.

3.1.3 Voltage Standing Wave Ratio (VSWR):

It is the measure of mismatch between load and transmission line. It is a way to measure transmission line imperfections. The desirable VSWR range of 1 ¡ VSWR ¡ 2 is desired for good antenna operation of any designed antenna.



(a) First



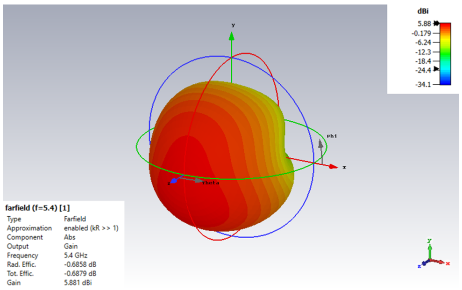
(b) Second

Figure 3.3: (a) VSWR vs. frequency plot of designed circular patch antenna dielectric material of Arlon AD 350. (b) VSWR vs. frequency plot of designed circular patch antenna dielectric material of FR-4.

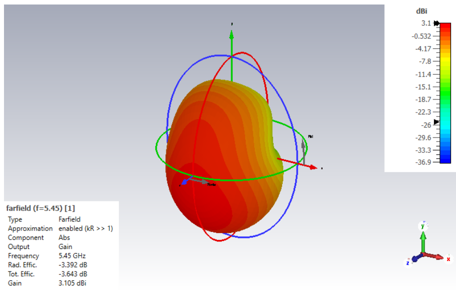
From figure 2.3(a,b) below, the designed circular patch antenna achieved a VSWR of 1.044 for Arlon AD 350 and 1.426 for FR-4 at the resonance frequency. The VSWR values of 1.044 , 1.426 indicate good impedance matching.

3.1.4 Gain:

The gain of an antenna is the measure of the antenna efficiency. It describes how far signals can travel through space. The 3D polar plot of the simulated antenna design is shown in figure 2.4(a,b) below.



(a) First



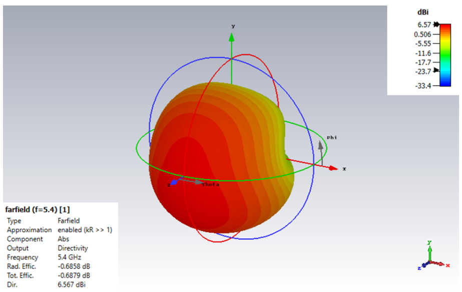
(b) Second

Figure 3.4: (a) 3D Gain plot of simulated circular patch antenna Arlon AD 350 dielectric. (b) 3D Gain plot of simulated circular patch antenna FR-4 dielectric.

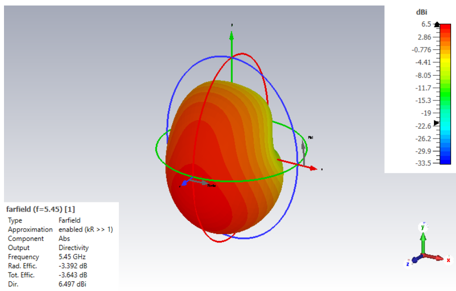
From the 3D polar plot shown in figure 2.4(a,b) , the gain of the designed antennas is 5.881 dBi for circular patch antenna Arlon AD 350 dielectric and 3.105 dBi for circular patch antenna FR-4 dielectric, at the resonant frequency of 5.4 GHz.

3.1.5 Directivity:

Is the measure of the ability of the antenna to radiate energy in a particular direction.



(a) First



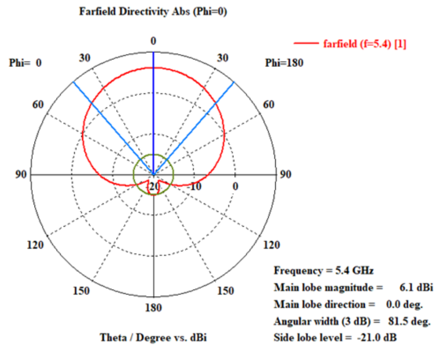
(b) Second

Figure 3.5: (a)3D Directivity plot of simulated circular patch antenna Arlon AD 350 dielectric. (b) 3D Directivity plot of simulated circular patch antenna FR-4 dielectric.

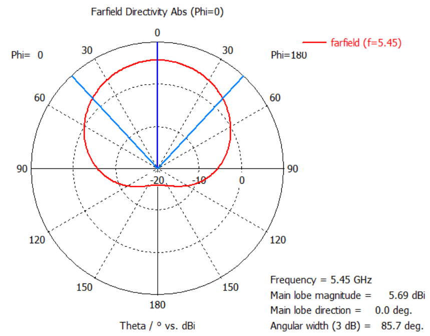
The maximum directivity figure 2.5, obtained for Arlon AD 350 dielectric material, is 6.567 dBi, and for FR-4 dielectric, is 6.497 dBi .

3.1.6 Radiation Pattern:

The radiation pattern of an antenna describes the shape and direction of the beam of electromagnetic wave from the antenna. Figure 2.6(a,b) presents the E-plane (phi=0 deg, x-z plane) and Figure 2.7(a,b) H-plane (phi=90 deg, y-z plane) radiation pattern of the designed circular patch antenna in polar plot.

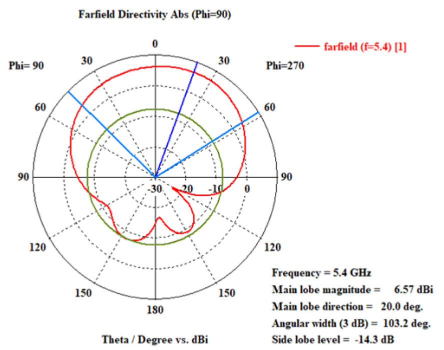


(a) First

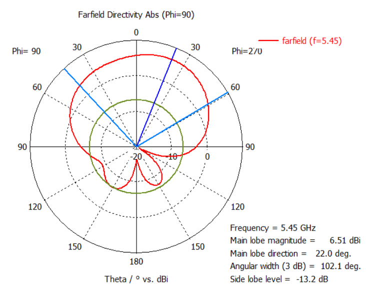


(b) Second

Figure 3.6: (a) Radiation Pattern of circular patch antenna Arlon AD 350 dielectric (E-field). (b) Radiation Pattern of circular patch antenna FR-4 dielectric (E-field).



(a) First



(b) Second

Figure 3.7: (a) Radiation Pattern of circular patch antenna Arlon AD 350 dielectric (H-field). (b) Radiation Pattern of circular patch antenna FR-4 dielectric (H-field).

3.1.7 Antenna Efficiency:

The antenna efficiency of the designed circular patch antenna is an important parameter that expresses the ratio of the total power radiated to the net power received by the antenna. In this research work, the radiation efficiency of the designed circular patch antenna is 85.35 % for circular patch antenna Arlon AD 350 dielectric, and 45.5 % for circular patch antenna FR-4 dielectric.

3.2 Summary of simulation results and analysis:

The summary of the simulation results of the designed circular patch antenna in this research work is shown in table 2.2

Table 3.1: Summary of simulated results of circular patch antenna

Materials	Arlon AD 350 dielectric	FR-4 dielectric
ε_r	3.5	4.3
Frequency (GHz)	5.4	5.4
S_{11}(dB)	-33.35	-15.10
Bandwidth (GHz)	0.1333	0.1736
VSWR	1.044	1.426
Directivity (dB)	6.567	6.496
Gain (dB)	5.881	3.105
Efficiency %	85.35%	45.5%

Table illustrates the performance parameters of the designed circular patch using the basic antenna parameter characteristics such as resonant frequency, return loss (S11), bandwidth, VSWR, gain, directivity, and efficiency.

3.3 Conclusion:

As a result of this study is to simulate a circular patch antenna for Ultra-Wide Band by using CST software at a center frequency (5.4GHz) for two substrates: Arlon AD 350 dielectric and FR-4 dielectric. The result is as below:

S11 -33.35 dB, VSWR 1.044, and Directivity 6.567 dBi for Arlon AD 350 dielectric.

S11 –15.10 dB, VSWR 1.426, and Directivity 6.496 dBi for FR-4 dielectric.

The dimension of the antenna also decreases for the higher values of the dielectric constants. Among the two dielectric materials used, FR-4 has the minimum gain (dBi) but it showed the highest bandwidth. The overall performance of the circular patch antenna is significantly influenced by the different substrate materials.

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