POLITECNICO DI TORINO

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Master's Degree Thesis

Characteristics of Materials Used for Printed Antennas for 5G Networks: Electric and Thermal Properties

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ABSTRACT

Technological advancements have revolutionized the world in the last decade. It has taken us towards smartness and automation. Internet of things is one of the major aspects of today's technology. The key parameter which has been proved for the adoption of IoT is the communication system. Because one of the most critical parameters is how much time it takes to communicate. Fifth Generation(5G) has been proved a game-changer and provides us with many new applications like augmented reality, remote surgery, autonomous drive, etc. Implementation of 5G requires antennas with wider band utilization, high capacity, and gain. Antennas provide a major breakthrough in implementing the 5G.

The main goal of this thesis is to observe the features of different materials used for the printed antennas, which are also known as microchip antennas, usually, such devices are equipped with. The originality of printed antenna systems is driven by a wide range of material and production techniques. These innovations address primarily fabrication and usability challenges. However, the antenna's performance deviates from the technologies and materials employed in the printed antenna field. Material properties depend on their molecular structure, type of bonding, and how much amount is used. The dispersion of materials can produce a frequency shift in the resonant frequency of antennas. These changes are discussed in the later section.

With a proper selection of material characteristics, I have observed a significant improvement in my outcomes compared to the earlier work as discussed in the results section. By making a comparison, in the case of Planar Inverted-F Antenna (PIFA), I encountered a hyperbolic curve in the frequency, and the PIFA antenna outcomes were also enhanced in my research over prior work. This is one of the results that I have discussed here and in the later section, I have explained in detail the parameter that has proven fruitful in improving the previous work. As a result, in our research, we focused on three antennas that behaved substantially different in terms of frequency and magnitude.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS

IoT	Internet of Things
PIFA	Planar Inverted-F Antenna
DC	Direct Current
RFID	Radio Frequency Identity
VSWR	Voltage Standing Wave Ratio
GAF	Graphene Assembly Film
MIMO	Multiple Input Multiple Output
PCB	Printed Circuit Board
5G	Fifth Generation
6G	Sixth Generation

Chapter 1

Introduction

1.1 Introduction

As a result of the growth in wearable devices and Internet of Things (IoT) frameworks, the need to communicate wirelessly undersize and shape constraints has become an essential and pressing research issue [1]. The design of a flexible antenna for a given application depends on the application itself, substrate material, fabrication technique, antenna design, and environment in which the antenna is to operate. To fully appreciate the design constraints and design space, we explore these factors. Once we are thoroughly apprehensive of the issues involved, we are better positioned to decide the direction of our research and the problems we are likely to encounter.

Modern 5G network promises high speed, low latency, and high throughput communications. These characteristics enable novel applications like smart cities, remote virtual surgery, entertainment, healthcare, industrial monitoring and control, and defense [2]. One of the limiting factors in these applications is form factor and weight. Smaller and conformal form factors and lighter weight are desirable properties. One of the defining technologies in this backdrop is flexible electronics. The advantages include conformity, lightweight, lower power consumption, portability, lower costs, and easy disposal. Owing to these factors and their usage in emerging technological fields, the market size of flexible electronics is estimated to the tune of over 40 billion dollars [3].

These systems would require a flexible antenna for wireless connectivity. The flexible systems, e.g., in the form of wearable devices, demand a flexible antenna system. This has led to increased research in this area. Specifically, biomedical applications require those antenna systems should be relaxed. Often scenarios involving wearable devices or other biomedical applications such as vital signs monitoring, organ regulation, interfaces to neural signals, gait analysis, and drug delivery dictate that the antenna be conformal to curvilinear surfaces, small, and stretchable. The antenna must continue to perform as per specifications in such an environment as an additional constraint.

Apart from wearable and biomedical applications, defense, smart cities, industrial monitoring, satellites, intelligent cars, aviation, and countless other application areas present scenarios that demand that antenna systems be conformal, miniature, flexible, or possess all these traits. Environmental constraints are always at play. For example, in defense, extreme temperature variations, satellite harsh radiations, industrial monitoring rigidity and variation in process parameters, aviation height, and atmospheric variations, etc., must be considered when designing a flexible antenna system [4].

To fully appreciate the vastness of such issues, we overview the techniques, materials, methods, and designs of antenna systems. This overview is intended to be general and cover the state of the art in flexible antenna design. We cover each facet described above separately and then look at the interplay of these characteristics in designing any system in an optimum way.

We start with materials and discuss conducting and substrate materials currently in use. We then consider different fabrication techniques. Fabrication techniques are followed by different frequencies for which an antenna system is required. This is followed by other design techniques that are employed for such frequency bands. We then cover some specific application areas that bring these techniques together to fulfill the constraints discussed earlier. Finally, once we can put together a system, it's time to test the performance. In the scenarios outlined above, we need to determine antenna radiation characteristics under various scenarios, e.g., temperature, deformation, etc. We overview some of the performance evaluation techniques that can be useful in our context. In the concluding remarks, the research interest that can be explored is presented.

1.2 Materials

Any antenna system is composed of conducting material supported on a substrate. Substrate selection is based upon

- Dielectric characteristics that affect the radiation mechanism (dielectric constant and loss tangent)
- Mechanical deformation as bending, conformance, and twisting that dictates how much the antenna system is conformal to the given surface and application
- The capacity of a material to be miniaturized
- Endurance to the external environment as temperature etc.

In this study, we consider conducting element effects antenna characteristics such as radiation pattern, bandwidth, etc. These characteristics are dictated mainly by the Conductivity of the material being used [5].

1.3 Conductive Materials

It is desirable to use highly conductive materials for the antenna and its feed [6]. This would result in better radiation patterns, efficiency, bandwidth, etc. However, for inflexible antenna systems, resistance to performance degradation due to mechanical deformation is also desirable. To accommodate these characteristics, conductive nanoparticle-based materials are used. Several materials and their features are summarized below

1.4 Metallic Nanoparticle Inks (NP-Inks)

NP inks are made using metallic conductors, their alloys, or oxides. The particles are designed with varying shapes and sizes. This tunes their optical, thermal, and conductive properties. Metallic NP inks are usually inkjet and aerosol jet printable. They have a high sintering temperature which renders quite a few substrates unusable. There must be a compromise between stretchability and Conductivity. Deforming usually degrades performance [7].

Table 1.1: Explaining the materials, strengths, weaknesses, and usages

Materials	**Strengths**	**Weakness**	**Usage**
Copper nanoparticle ink	The Conductivity of 58.8 $\times 10^6$ S/m [25] at 293.15 K. Ductile and malleable. One hundred times cheaper compared to silver. Commercially available.	Oxidation when exposed to air or during sintering. Nanoparticle inks have a stretchability vs conductivity trade-off. Printing using sintering requires noble gasses or vacuum, which is expensive and time-consuming	
Silver nanoparticle ink	It does not oxidize; Conductivity of 62.9 $\times 10^6$ S/m at 293.15 K. Can be printed using inkjet and aerosol jet printing on	Tarnishes when exposed to hydrogen sulfide, which might be present in the air, High costs	strain gauges,[5,50]patch antennas,[51] 3D antennas,[52] radio-frequency

	various substrates. Sintering temperatures vary from 100 to 300 º C. Electrical, chemical, and optical properties are tunable by varying particle shapes and sizes. Commercially available.		identification (RFID) tags[53]
Gold Nanoparticle ink	The Conductivity of 41.0 × 10^6 S m−1[25] at 293.15 K. Highly ductile, malleable, inert, does not oxidize, does not tarnish, easily sintered hence easily printed by inkjet or aerosol-based printers. Highly tunable particles. Commercially available.	Very expensive, due to higher sintering temperature substrates such as PET cannot be used.	electrochemical sensors[92] wearable resistant to high salt concentrations[88], printed organic thin film transistors (OTFTs) applications, electrodes arrays,[92,94] microelectrode arrays (MEAs) for biosensing applications[88] interdigitated electrodes (IDEs).[88
Aluminum nanoparticle ink	The Conductivity of 35.5 × 10^6 S/m[25]at 293.15 K, inkjet and aerosol jet printers are used. Corrosion-resistant. Commercially available is somewhat limited.	Higher sintering temperatures restrict a variety of temperature-sensitive substrates	Conductive line printing on PV cells

Cobalt nanoparticle inks	Conductivity of 17.0 × 10^6 S/m[26]. Ferromagnetic, Corrosion resistant, high permeability, and permittivity.	High sintering temperature, not available commercially.	Applications requiring interaction with EM waves. radio frequency absorbers, antennas, magnetic sensors, filters, resonators, and phase shifters.[104–106]
Nickel nanoparticles ink	Conductivity of 14.3 × 10^6 S/m[26]. Ferromagnetic, corrosion-resistant, commercially available, inkjet printable	High sintering temperature	Coating other inks that are susceptible to oxidations, such as copper
Palladium nanoparticle ink	The Conductivity of 9.5 × 10^6 S/m. Screen printable. Commercially available	High sintering temperature, is very expensive, and rare.	Unique reactions with hydrogen allow usage as gas sensors, electrodes for fuel cells, pH sensors, conductive tracks, thin-film transistors, electrochemical sensors,
Platinum nanoparticle ink	The Conductivity of 9.1 × 10^6 S/m. Ductile, malleable, inkjet printable, resistant to corrosion and tarnishing, inkjet, and aerosol jet printing,	Very little commercial availability, very high sintering temperatures	MEMS sensors for gas, conductors for high-performance PV systems, and sensors for biochemical processes.

Copper-nickel alloy NP ink	Reduced Conductivity, inkjet, and aerosol jet printable	Limited commercial availability	Strain gauges
Copper-Oxide NP ink			
Iron-Oxide NP ink	Excellent magnetic properties such as high permeability, reasonable saturation	Research phase	Inductors and other printable magnetic components
Indium Tin Oxide NP ink	Transparent conductive inks, good chemical inertness, good substrate adhesion	Research to make ITO NP ink printable	Transparent electronics, touch panels
Cu-Ag and Cu-Ni Bimetallic NP Ink	Copper is coated with thin silver or nickel surface. Solves oxidation of copper and avoids the high cost of silver. Nickel coating further reduces the cost	Not available commercially, challenging to print,	

To circumvent the stretchability problem, the metals are woven into fabrics using a variety of methods such as Electroplating, embedding, and weaving. Fibers and clothing have a variety of desirable features. They are stretchable and breathable structures. They are resistant to wear and tear. They can withstand rough conditions. They are resistant to deformity and structural failures. With advances in nanotechnology, it has become feasible to embed fibrous structures with electronics. However, we are going to review the materials that make conductions possible in fibers. Commonly used metals are carbon, nickel, copper, gold, silver, or titanium. Methods used are Electroplating, autocatalytic chemistry, NP ink printing, or vapor deposition. Some of the metal-infused fibers are listed below.

Table 1.2: Metal-infused fibers used

Ni/Ag-plated fibers	The coatings are made using electro or electroless plating. The weight of the coating as the percentage of fiber is controlled to control the Conductivity of the finished product. The coating weight has to be optimized against the structural properties of the fiber.
Electron (copper-based nylon fabric)	Flexible and Easy to design
Non-Woven Conductive Fibers	Easy to manufacture
Adhesive copper	Thermal stability
Copper tapes	Better static dissipation, heat resistance, and stability, and not easy to tear.
Copper Cladding	Low thermal movement, radio frequency shielding, ventilation, low maintenance, and lightning protection.
Polyaniline (PANI)	Conductivity is a wide and controllable range, melting material, and transparent electrically conductive product.
Graphene paper	Immensely tough and stronger than steel and remarkable flexible.
Graphene oxide ink	Stable in water suspension
Stretchable fabric	Immensely resistant and flexible

1.5 Substrates

The desirable properties of substrate materials have been mentioned earlier. Below we give an overview of some substrate materials being used in flexible antenna design.

Table 1.3: Substrate materials used in flexible antenna design

Materials	Strengths	Weakness
PET	Flexible	Low resistance capacity
PEN		
Polyimide	Excellent high radiation resistance and temperature properties	Expensive and poor resistance to alkalies and hydrolysis
PDMS	Easy fabrication, not expensive, and high gas permeability.	Difficult to integrate electrodes
PDMS with glass microsphere		
Liquid Crystal Polymer	Highly heat and chemical resistance and insulating properties.	Not suitable for a bright environment.
Fleece Fabric	Comfortable, lightweight, and flexible.	Not windproof
Cordura	Thermal stability, color fastness, and simplicity in leaving.	Heavy fabric and expensive.
Woolen felt	Hold moisture without feeling wet and significant thermal insulator	Scratchy and uncomfortable
Felt	Warmth and resilience	Cleaning felt clothing is problematic
Cotton/Polyester	Static and less prone to filling	expensive

1.6 Fabrication Techniques

Antenna performance is determined by the fabrication method. Commonly used techniques are inkjet printing, screen printing, and wet etching. Designing antenna, analysis, and fabrication is the most significant challenge in terms of cost. To analyze, a fabricated antenna design, measurement equipment, and different RF expensive test are needed. RF generator, vector analyzer, spectrum analyzer, and RF power meter are these devices that might include. Each of these items can potentially exceed the cost of a new luxury automobile. An antenna design should first be technically manufactured and focuses on the conceptual design once it has been verified. Current antennas are indeed implemented in the form of a Printed Circuit Board (PCB). Because the equipment necessary to make PCBs is so costly, most manufacturers outsource their gadget fabrication to third-party PCB firms. This procedure can be somewhat costly, particularly for prototypes and small production. Finally, due to several complicated mathematical principles connected to electromagnetic wave propagation, as well as the unique design concepts relevant to the intended antenna application, a solid mathematical foundation, as well as a strong RF engineering experience, is essential to building antennas.

Chapter 2
Literature Review

This chapter discusses the technical background and relevant literature on which the implementation of the project depends. In this chapter we will evaluate different properties of the antenna, materials use in the antenna, fabrication techniques, and design antenna for 5G application.

2.1 Background

Future technologies like Fifth Generation (5G) and Sixth Generation (6G) need greater capacity antenna, steer- availability, high gain, and wider spectrum utilization. This is owing to the previous technologies' generation limited spectrum usage. In fact, traditional antennas are unable to service the new bands of frequency because of manufacturing and installation, difficulties, particularly for the smaller size. Graphene materials usage allows for the antenna to be thinner and smaller while yet producing frequencies. Therefore, an antenna of graphene was investigated at a 15 GHz frequency in a single and array element [1]. The antenna of high frequency has a wide bandwidth and was stimulated by a collinear waveguide for simple screen-printing manufacturing on one surface. To boost the gain and enhance the radiation, the defective ground structure was used in an array-based element. The results of this study demonstrate the printed antenna of a single graphene element. Finding again, efficiency and bandwidth of 2.87dBi, 67.44%, and 98.64% respectively. However, the array element had a somewhat superior efficiency of 82.98%, roughly the same bandwidth of 48.98%, but better gain than the single element of 8.41dBi. Furthermore, it had a 21.2 beam width and 0 to 39.05 beam capability of scanning. Results demonstrated that graphene material can be used in 5G.

5G technology is expected to provide better performance and coverage than the previous generations. For long-distance communication millimeter and high-frequency waves experience propagation loss, more loss in energy, and penetration loss. To overcome these problems a graphene array antenna is proposed to achieve high gain for long-distance communications [2]. In this study, the author conducted three types of substrates to achieve more than 7 dBi gain. The obtained gain in this study is better than the current state-of-the-art studies. Finally, the proposed antenna is consuming a small number of elements to provide high gain.

Design 5G antenna needs all-band configuration, radiation concentration, multi-purpose beamforming, low loss, and precise beam coverage. Furthermore, 5G antennas must have wideband and low side lobe features to boost data transmission rate and spectrum capacity, implement spectrum capacity, and optimize channel utilization. Consequently, millimeter-wave communication has gained the interest of academics and specialists due to its benefits of the vast spectrum of resources, miniaturization, high directivity, and high resolution. In paper [3], the author proposed an mm-wave antenna array of 128 elements based on GAF for mobile communication, that exhibits pleasing wideband and sidelobes performance. The Chebyshev current distribution GAF array antenna operates at 25.92GHz, with a measured -10dB impedance bandwidth of 24 to 27.82 GHz, covering the mm-wave communication band. The radiation patterns of sidelobes of the GAF array antenna are lower than -20 dB. The gain and radiation pattern of the GAF array antenna are presented and measured in the same as their copper counterparts.

Because of their low cost, lightweight, and flexibility, graphene antennas and related microwave devices have gotten a lot of attention. However, due to the limited conductivity of graphene materials on a macroscopic scale, their results are frequently unsatisfactory. An antenna array built of flexible graphene materials is created and reported in [4], with the capability to be used in 5G mobile communications. At 3.51 GHz, the antenna array has a high gain of 6.77 dBi and an outstanding return loss, which is analogous to the copper version. Furthermore, the graphene antenna and the copper antenna have similar radiation patterns.

Multiple Input Multiple Output (MIMO) antenna system improvements require reducing the coupling between antenna elements. The author in [5] proposed a graphene MIMO antenna for 5G applications. An Isolation strip and Graphene Assembly Film (GAF) frequency enhance the antenna element isolation. The realized gain of the GAF antenna element operating at 3.5Ghz is demonstrated to be 2.87dBI. The decoupling structure enhances the MIMO antenna isolation by more than 10 dB while also correcting the radiation. With an interval of 0.4λ, the isolation of the antenna element is more than 25dBi. The decoupling and GAF structure are effective equipment for 5G communication, as demonstrated in the results of this study.

To improve the microstrip antenna's electrical performance at terahertz frequency a constructive dielectric constant substrate material has been investigated in [6]. In this study, the substrate materials that are frequency-dependent are analyzed and the result was compared to a commercially available simulator based on the finite integral technique, CST Microwave studio. At 600 GHz, the rectangular microstrip patch antenna input impedance and electrical performance substrate material on two-layer were also analyzed. The antenna's input impedance characteristic was manipulated, resulting in a slow wave shape. The performance of this slow-wave structure was tested at 542 GHz, and it was shown to be improved without increasing the overall size of the proposed antenna.

An E-shaped microstrip patch antenna has been proposed in this research article [7]. Epoxy-kevlar and FR4-epoxy materials are used to create an E-shaped microstrip patch antenna. Epoxy-kevlar and FR4-epoxy have 3.6 and 4.4 permittivities respectively. The proposed antenna radiation pattern, return loss, and gain reveal that it offers potential qualities for a variety of wireless communication applications. The consequences of modifying the permittivity of the substrate are also investigated in this research article.

To design and implement staggering material graphene antennas of terahertz frequency with amazing electrical properties is an extensive idea. Recently, a patch antenna of graphene materials in the field of communication is gaining more interest because of its small size in the micrometers range at the THz frequency band. The author in [8] designed a graphene material circular patch antenna to operate in the frequency range of 6.8-7.2 THz. Silicon nitride, polyimide, silicon dioxide, and quart were used as substrate materials, and the Patch antenna performance was evaluated using 2D and 3D radiation patterns of output gain, voltage standing wave ratio (VSWR), and return loss. When compared to alternative substrate materials the results demonstrate that employing polyimide as a substrate material leads to a great performance with a gain of 16.7 dB.

2.2 Related Work

Previously we outlined various methods that can be classified as additive manufacturing and direct writing methods. The review of these techniques has concluded that in general, the traditional techniques are superior to these novel manufacturing techniques. The novel methods allow novel design space to be tapped which is not available with traditional methods. This allows for performance enhancement but the design space in terms of electrical and mass production capabilities still needs to be explored and bridged before taking full advantage. These include permittivity, conductivity, permeability, loss tangent, malleability, surface oxidation, strength, etc. An overview of properties in terms of the structure reveals that non-uniform molecular structure results in degradation of both electrical and mechanical properties. Further, the in-ability or cost prohibitiveness of printed or additive materials does not allow for the formation of thicker substrates or conductors. This adds to property deterioration [1].

In [2] the authors have evaluated spray-painted antennas. The results show promise as various simulated and measured parameters are not only in agreement, but the results are worthwhile in themselves as well. But compared to traditional materials and techniques these still need to improve by a margin [e.g., any reference with folded dipole antenna using usual materials].

The printable antenna array and other structures for different techniques and inks have been studied in [3]. The authors experimented various with various ink formulations and printing methods. Copper and silver nano-particle inks were employed with aerosol, inkjet, and screen printing. The results, though promising still need to improve for commercial usage. The authors also experimented with the textile antenna. Copper tape, copper laced thread, and conductive spray were applied to textile materials. Performance shows a marked decrease, especially in terms of radiation efficiency.

Conductive ink with screen printing is investigated in [4]. The authors used various inks and pure copper for various demonstrators. The copper inks and copper-based design performed visibly better than other options. The performance is measured in terms of reflection coefficient and radiation efficiency.

Another inkjet printer antenna design for Radio Frequency Identity (RFID) is investigated in [5]. RFID is an important application of antenna systems. The effect of printed materials vs. bulk material is considered by the authors. It's found that printed copper can achieve the performance of up to 80 percent of bulk copper. It is also found that copper-based antennas perform better than bulk or sprayed silver. A simple analytical model is developed that has reasonable accuracy with respect to MOM simulation.

In [6] a thorough review of the flexible and printed antenna is undertaken. The review considered materials, fabrication methods, designs, and applications. It concluded by pointing out the variety in all facets of flexible antenna systems. The variety is more like a jungle than a garden right now and every application developer has to navigate the landscape to successfully design a system for the application. The mass production ability for novel methods and techniques is still in earlier stages. The performance of printable antennae is improving and is sufficient for a variety of applications. Still, the performance gap compared to traditional methods is considerable.

Another application-specific review is [7] which extensively compared different materials and techniques for UHF RFID tags. The technique used is inkjet printing, which seems to be a popular choice in this review. A variety of materials as substrates are used. The variety came about by directly printing the antenna design on commercial products. The ink is silver-based with a polyimide film. The results are found to be satisfactory but inferior to traditional tags. Also, these tags are still expensive to print. The research showcases a promising application of printed antenna and RF technologies.

A printable antenna adds a new dimension to antenna design. The conformability to complex 3-D surfaces enhances performance by many folds. This is one of the areas where traditional antenna systems fall short of printable technologies.

In [8] a 3D partially reflecting surface is placed on a resonant cavity antenna which improved the performance by nearly 40 percent. In [9] graphene-based ink is used to design a slot antenna. The bandwidth of the antenna is about 500 MHz with a wide tunable frequency range. The tuning is done by applying a DC voltage. This capability is usually not found in traditional antennae. In [10] the researchers have designed a porous superstrate that enhances directivity for resonant cavity antenna by almost 7.2 dB.

Another exciting development being spearheaded by advanced materials in printable antennae is the electronic bang-gap structure. The EBG can excite a particular Bloch wave structure that can enhance radiation patterns. In [10] the authors realized an antenna using this phenomenon and an improvement in radiation efficiency is noted.

Chapter 3
Design & Implementation

This report considers the effects of materials for printable antenna for various designs for 5G communication. We would first present designs employing copper and standard substrates. We would then employ materials summarized in chapter 1 for the same design. We would then observe the changes in center-frequency, bandwidth, and radiation patterns.

3.1 Introduction

As discussed previously the novelty in printed antenna systems is driven by variety of choices in materials and fabrication techniques. These novelties solve issues mainly pertaining to fabrication and usability. However, the performance of the antenna deteriorates deviates for the technologies and materials used in printed antenna field. The research in this area has investigated various reasons and postulated the decrease in conductivity and non-homogeneity of the media as main reasons. In this report we would discuss the extent of such deviation or deterioration using simulation methods.

We have chosen 5G communication system as example application. Communication is one of the foremost applications that employ antennas other being sensing and radar. Communication is expected to be a major application in wearable market or printed antenna market. 5G communication system is a robust, versatile, and high-speed data communication protocol that is set to become a unified data communication protocol for the coming decade.

In this chapter we first review the effect of materials and fabrication technique on the performance of the antenna. We then present the design of commonly used three antennas for 5G communication viz. Patch, PIFA and Vivaldi antennae. Using simulation, we then employ variety of materials in the same design and observe the effect.

In short, the printable antenna community is actively probing novel methods to bring printable antennae in vogue. The advances are made on mechanical properties include stretchability, strength, and conformability whereas EBG structures can enhance efficiency of the radiation. The ability to print electronics and antenna simultaneously is a feature that is not present in traditionally etched/fabricated antennae. The spatial dimension and flexibility afforded in shaping the antenna design is still another feature usually not afforded by the traditional techniques. These properties, however, hints at niche applications where printable antennae are finding ever more applications.

When it comes to bulk properties, either electrical or mechanical, traditional techniques still rule the technology landscape. The performance is almost always better, and the mass production capability is an edge currently not afforded by advance printable methods. Traditional antennae are also cost effective both in terms of design and in terms of production. The mass markets are still in favor of copper on FR4 (or other common dielectrics).

However, as technology seeps deeper and dig harder at our lives we are coming to face with personalization issue, applications and techs tailored for individuals. Such a landscape is afforded only because of novelty in areas like printable antenna. In future we might find a material and technique that comes at par with bulk copper and FR4 with all the benefits of these materials and then some.

Hence, it is imperative to look how design space is managed for a particular design space. In this regard a comparative simulation study is usually not only first resort but offers valuable in-sights. We perform a simulation study for 5G communication antenna in following pages.

3.2 Patch Antenna Dimensions

A patch antenna has a curved coverage path and may stretch to a width of 30 to 180 degrees when hung on a wall. This sort of antenna is generally small and light, making it easy to hang on walls. It is normally covered in white or black plastic to blend in with the surroundings as shown in Fig. 3.1.

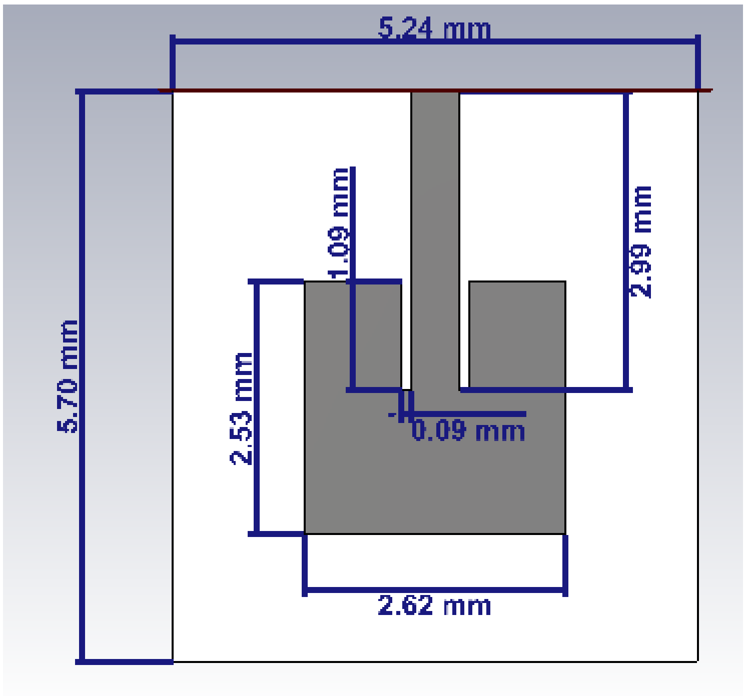


Fig. 3.1: Patch Antenna Dimensions

3.3 PIFA Antenna Design

An inverted-F antenna is a form of wireless communication antenna that operates mostly at UHF and microwave frequencies. It consists of a monopole antenna that is grounded at one end and runs parallel to a ground plane as shown in Fig. 3.2.

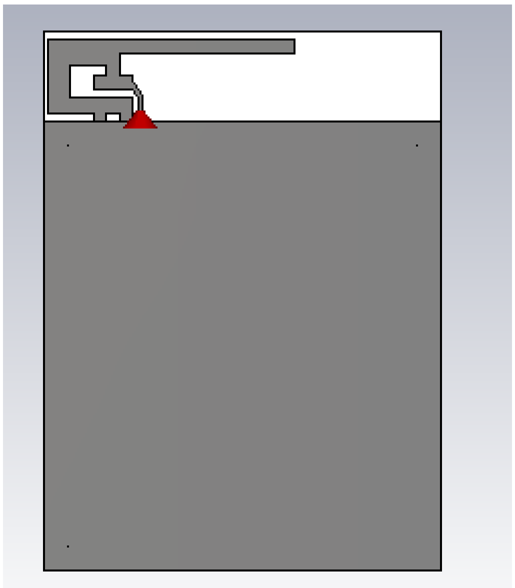


Fig. 3.2: PIFA Antenna Design

3.3.1 PIFA Antenna Dimensions

PIFA's overall dimensions are 21.72 mm x 18.5 mm x 4 mm. Because of its low profile, tiny size, and high gain, this antenna is ideal for placement on a cell phone. Ansys HFSS is used to model the proposed antenna's performance in terms of return loss, VSWR, and gain as shown in Fig. 3.3 (a).

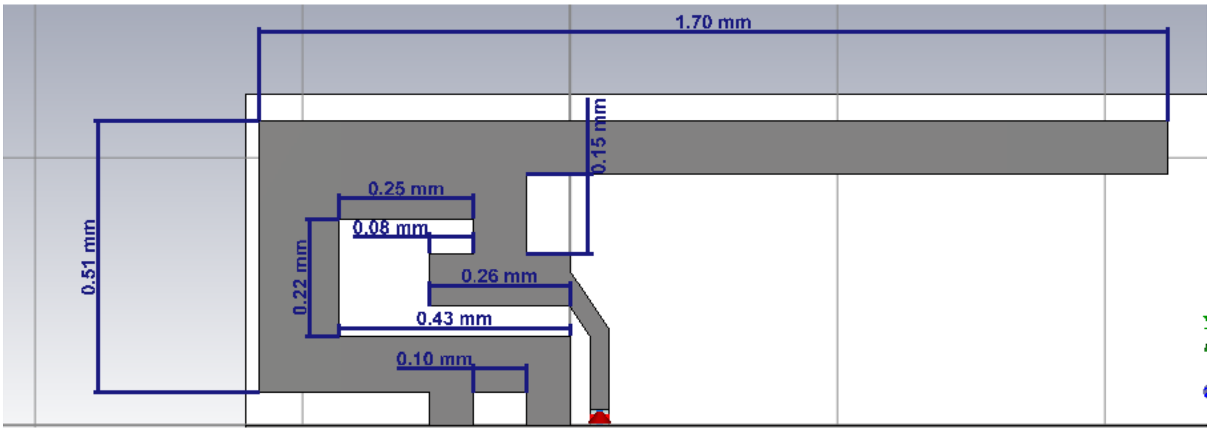


Fig. 3.3(a): PIFA Antenna Dimensions

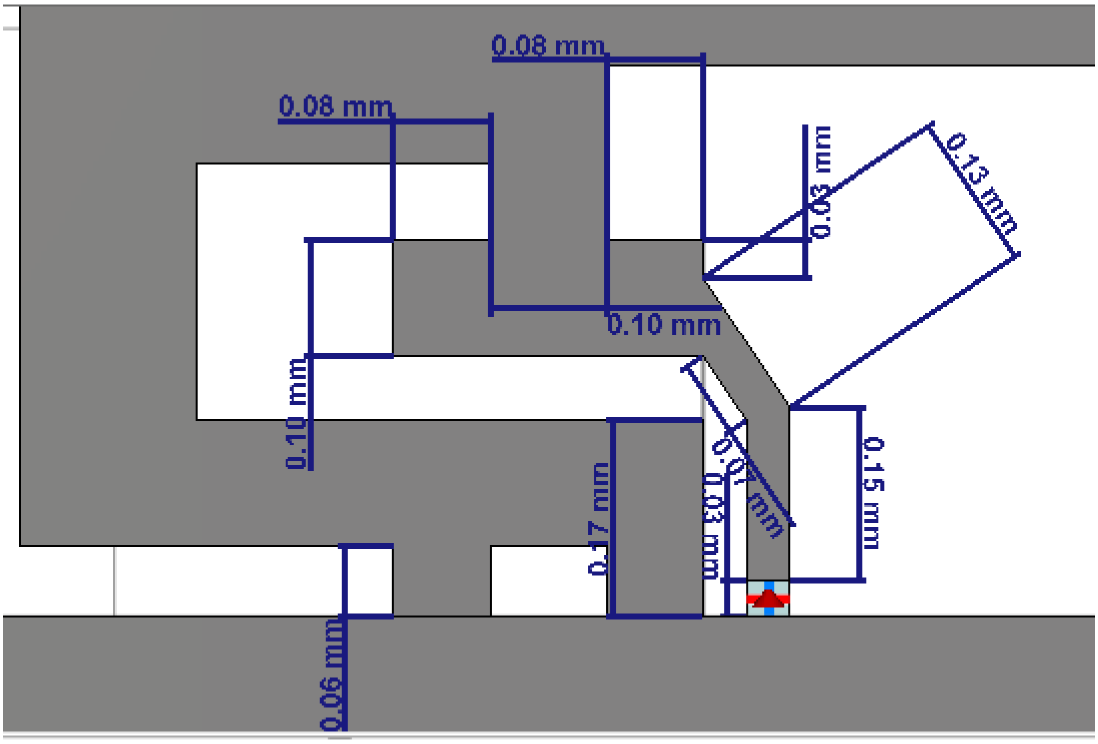


Fig. 3.3(b): PIFA Antenna Dimensions

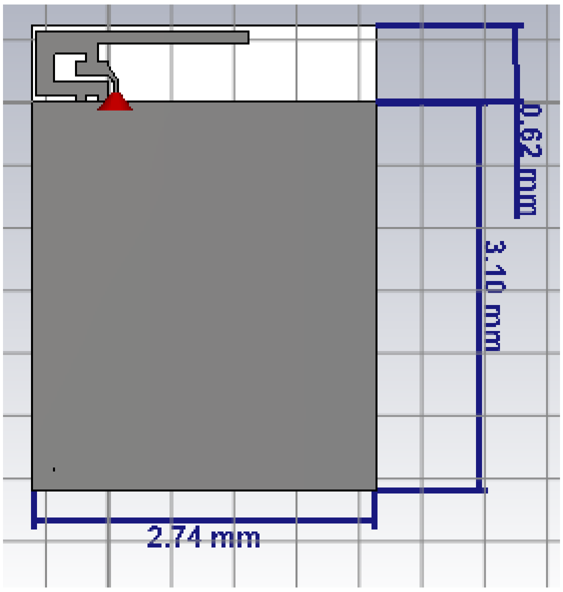


Fig. 3.3(c): PIFA Antenna Dimensions

3.4 Vivaldi Antenna Design

For wide band applications, a tapered slot antenna, commonly known as a Vivaldi antenna, is helpful. For the taper profile, an exponential function is applied. The goal of this model is to compute the far-field pattern as well as the structure's impedance as shown in Fig. 3.4.

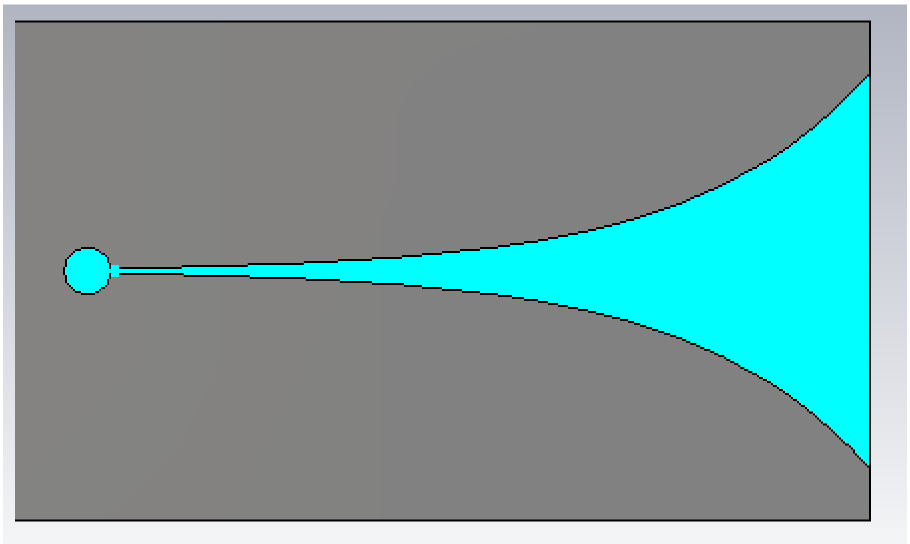


Fig. 3.4(a): Vivaldi Antenna Design

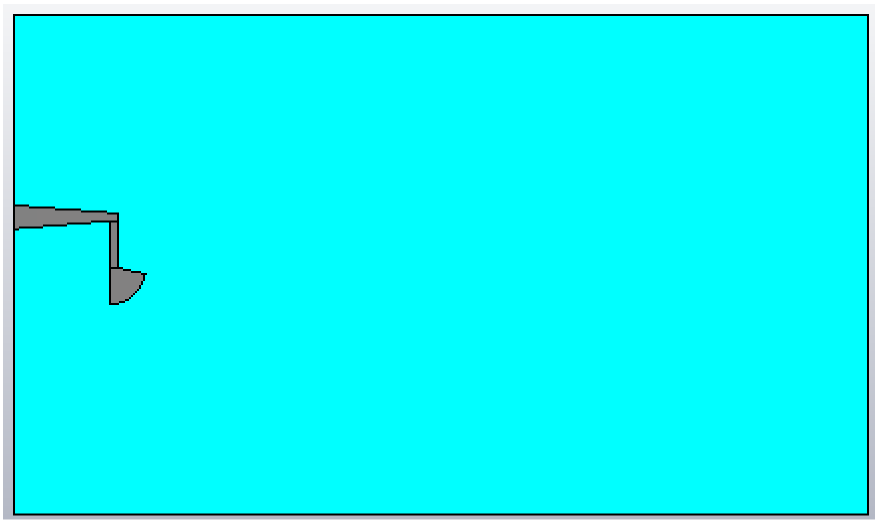


Fig. 3.4(b): Vivaldi Antenna Design

3.4.1 Vivaldi Antenna Dimensions

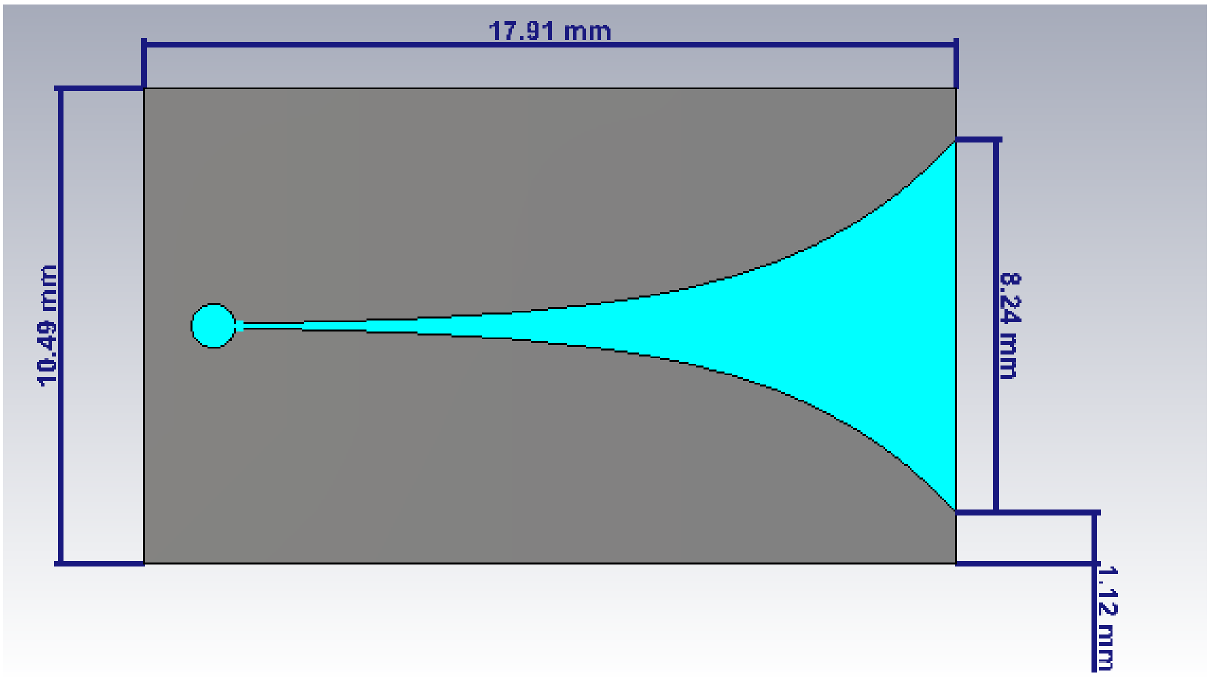


Fig. 3.5(a): Vivaldi Antenna Dimensions

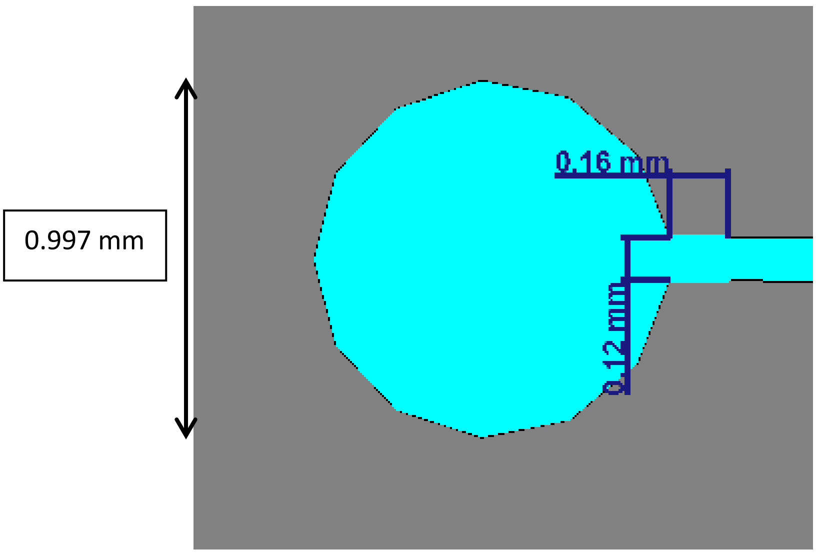


Fig. 3.5(b): Vivaldi Antenna Dimensions

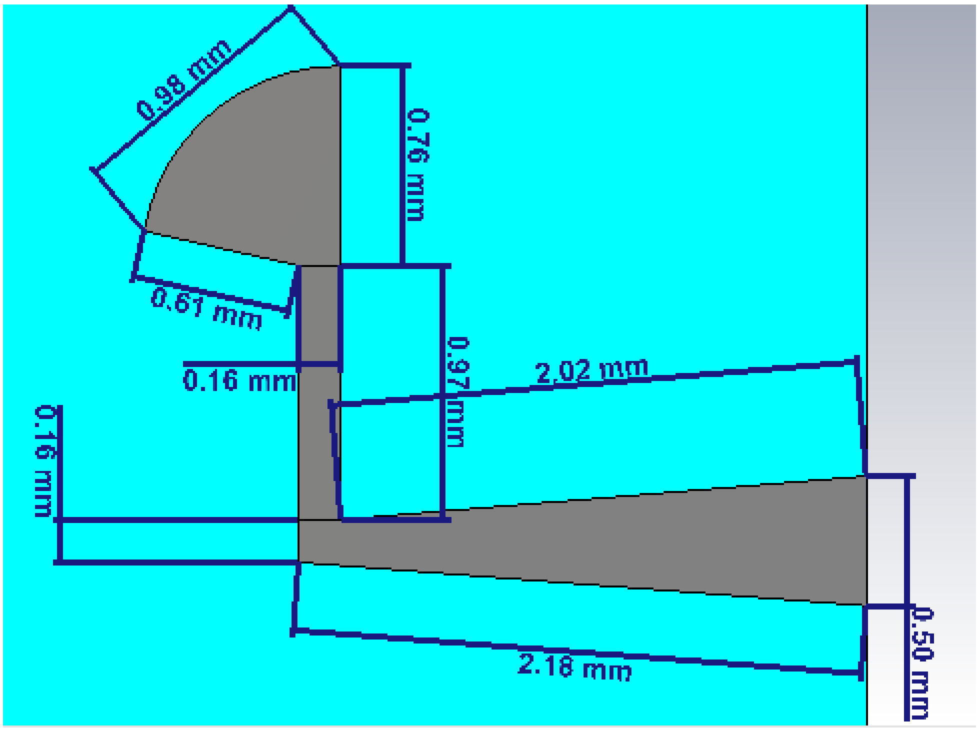


Fig. 3.5(c): Vivaldi Antenna Dimensions

3.5 Bending Analysis of All Three Antennas

Bending analysis of all discussed three types of antennas have been discussed as follows. All three antennas are designed on a thin substrate with thickness of 0.25 mm. so it is must to analyze the performance of the antenna on bending.

3.5.1 Patch Antenna Bending Analysis

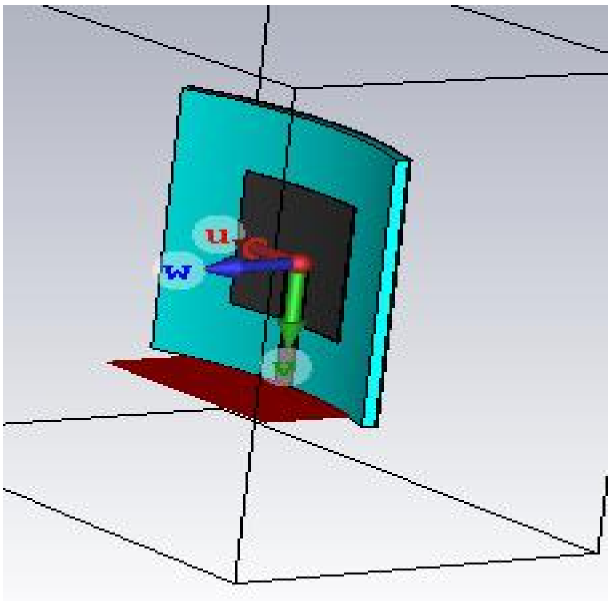


Fig. 3.6(a): Patch Antenna Bending Analysis

Bending analysis is performed on Patch Antenna in CST. When patch antenna is bended its response for different bending radiuses is shown below. It S11 response shows that antenna works well for bending radius up to 30 mm. which validated the good performance of antenna on bending.

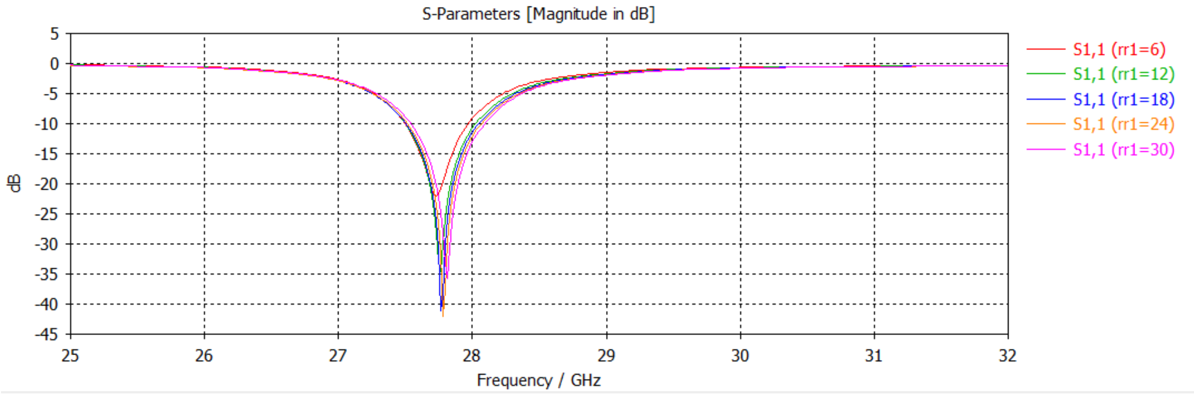


Fig. 3.6(b): Patch Antenna Bending Analysis

3.5.2 PIFA Antenna Bending Analysis

Bending analysis is performed on PIFA antenna in CST. When PIFA antenna is bended its response for different bending radiuses is shown below. It shows that antenna works well for higher bending radiuses. S11 plot is shown in Fig. validated the good performance of antenna on bending.

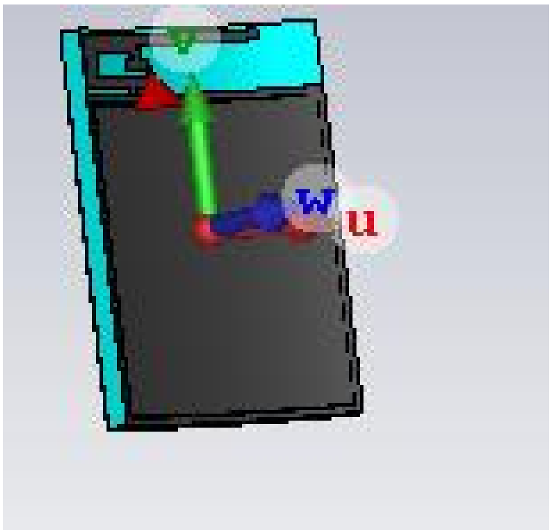


Fig. 3.7(a): PIFA Antenna Bending Analysis

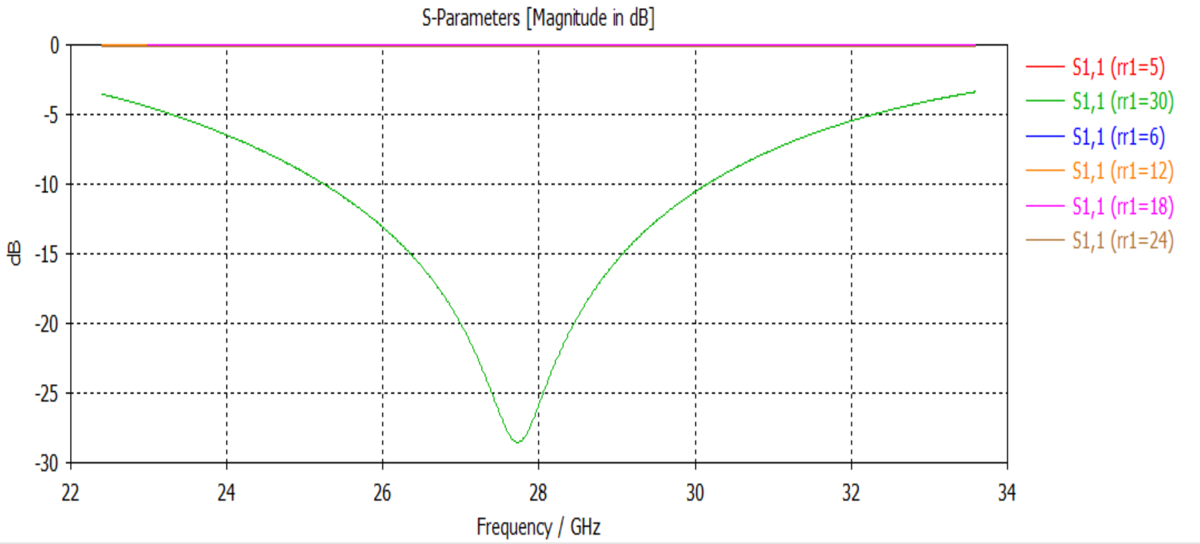


Fig. 3.7(b): PIFA Antenna Bending Analysis

3.5.3 Vivaldi Antenna Bending Analysis

Bending analysis is performed for Vivaldi antenna in CST. When PIFA antenna is bended its response for different bending radiuses is shown below. It shows that antenna does not perform well on bending, its bandwidth decreases on bending.

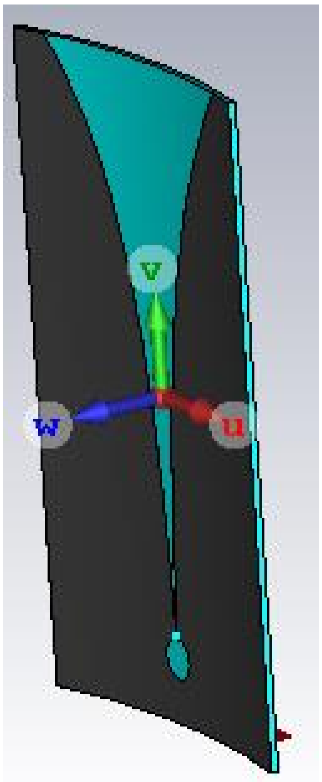


Fig. 3.8(a): Vivaldi Antenna Bending Analysis

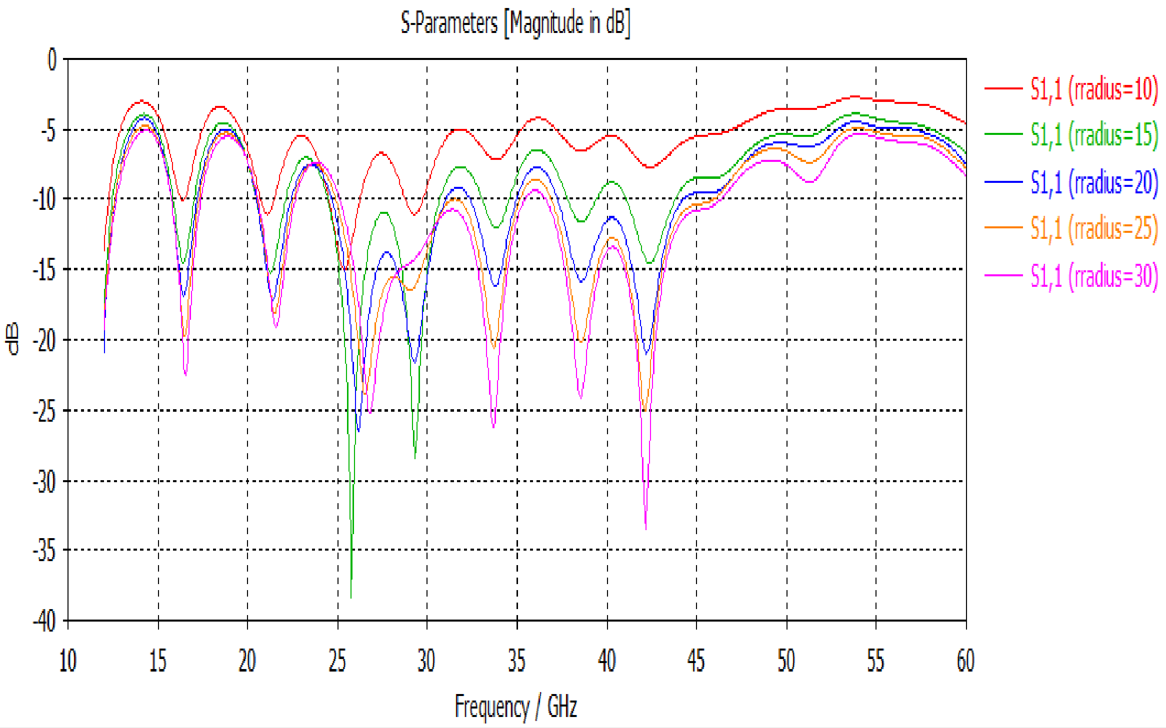


Fig. 3.8(b): Vivaldi Antenna Bending Analysis

Chapter 4
Results and Discussion

4.1 Patch: Voltage Standing Wave Ratio (VSWR)

The **Voltage Standing Wave Ratio** (VSWR) is an *indication of the amount of mismatch between an antenna and the feed line connecting to it*. This is also known as the **Standing Wave Ratio** (SWR). The range of values for VSWR is from 1 to ∞. A VSWR value under 2 is considered suitable for most antenna applications. The antenna can be described as having a "Good Match". So when someone says that the antenna is poorly matched, very often it means that the VSWR value exceeds 2 for a frequency of interest.

The VSWR of the proposed antenna is given bellow. It can be seen from the Fig. 4.1 that VSWR at 28 GHz is bellow 2 which means that antenna is well matched.

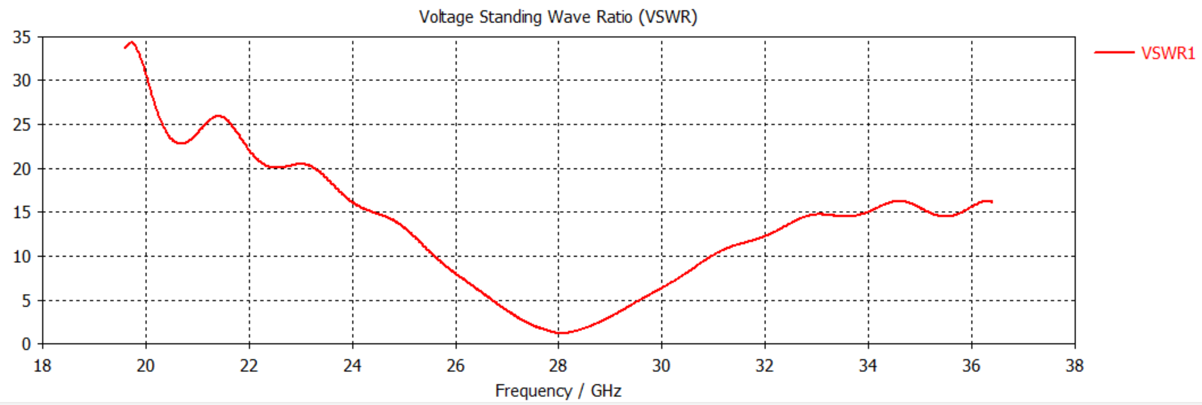


Fig. 4.1: Patch VSWR

4.2 Patch Antenna Results

Patch antennas results have been discussed in detail as follows. Different materials are used as substrate corresponding to that the change in the results is analyzed. Antenna is mostly judged based on three parameter 1) S11 2) VSWR 3) Radiation Pattern. All these results are discussed for each substate.

4.2.1 Patch Antenna with Substrate Rogers 5880 and Patch Material Copper

Reflection coefficient is the most important parameter to judge the performance of the antenna. It explains the amount of power reflected due to discontinuity in the transmission line. It is the ratio of the power reflected to the power incident. It's value less than -10 dB is considered as good.

A patch antenna is designed at 28 GHz. Fig. 4.2 shows the reflection coefficient of the patch antenna. It can be seen that S11 is less than -10dB at 28 GHz, which means that antenna is working at 28 GHz.

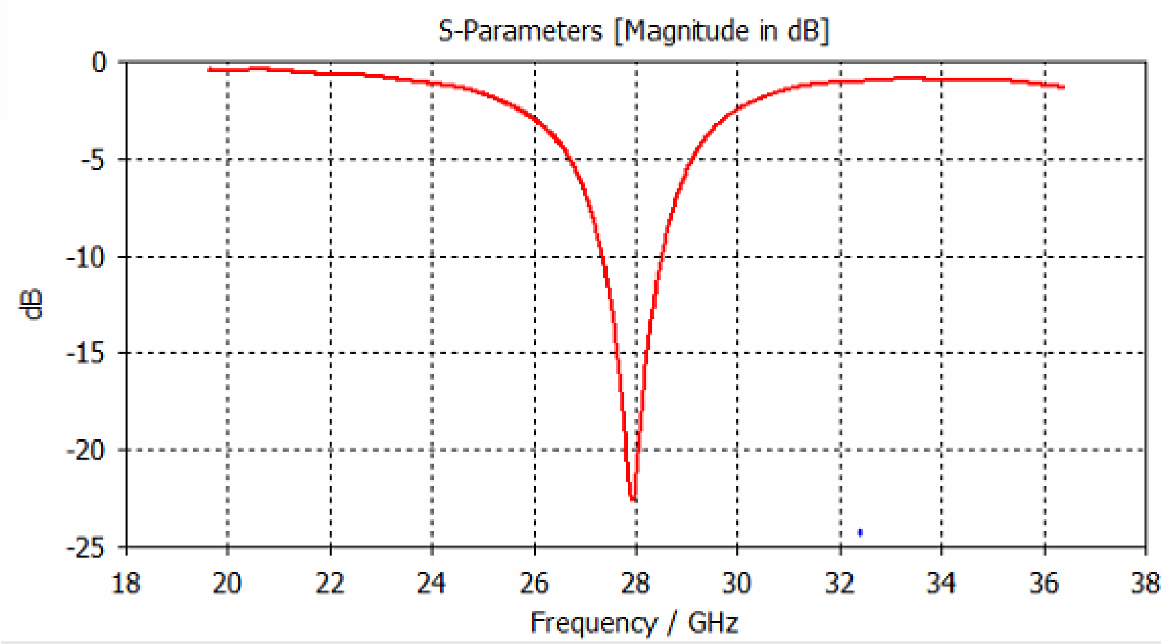


Fig. 4.2: substrate Rogers 5880 and patch material copper

Fig. 4.3 shows the radiation pattern of the antenna in E and H plane. Radiation pattern gives direction of the where the antenna radiates. By seeing the pattern, it can be estimated whether the antenna is omnidirectional or directional.

It can be seen from the Fig. that the antenna is radiating in specific direction with a gain of 7.7 dBi in E plane and H plane. The beam width of antenna is 84 degrees in E plane and 72 degrees in H plane.

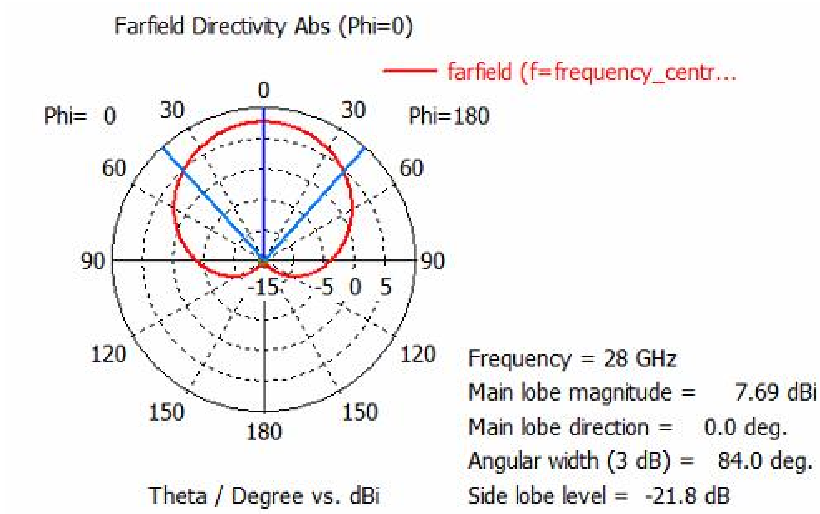


Fig. 4.3: Farfield directive Abs (Phi=0)

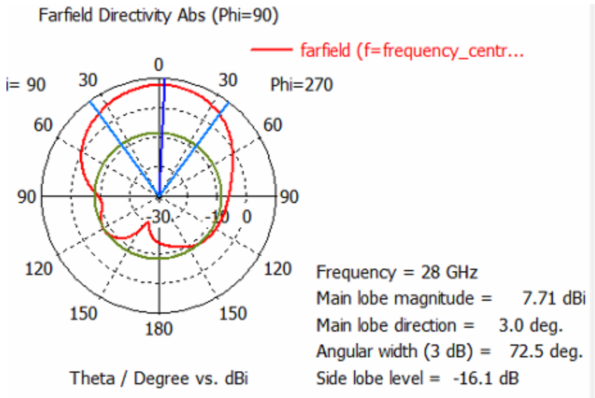


Fig. 4.4: Farfield directive Abs (Phi=90)

4.2.2 Patch with Substrate Fabric and Patch Ag NP

Now fabric is used as a substrate and Ag NP as a conducting material. It can be seen from the Fig. 4.28 that the S11 response moves toward higher frequencies. Because fabric has higher permittivity. Radiation pattern of the antenna is not changed with this change in materials. Its gain and beam width remains the same as for the rogers and copper.

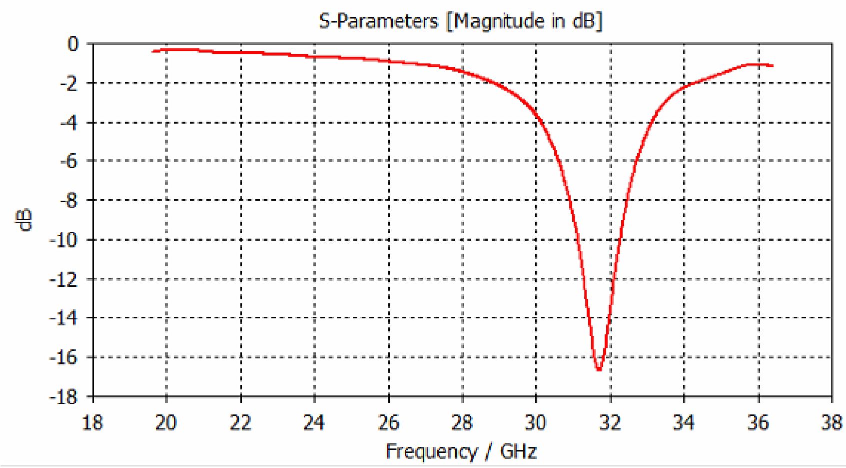


Fig. 4.28: Substrate Fabric and patch Ag NP

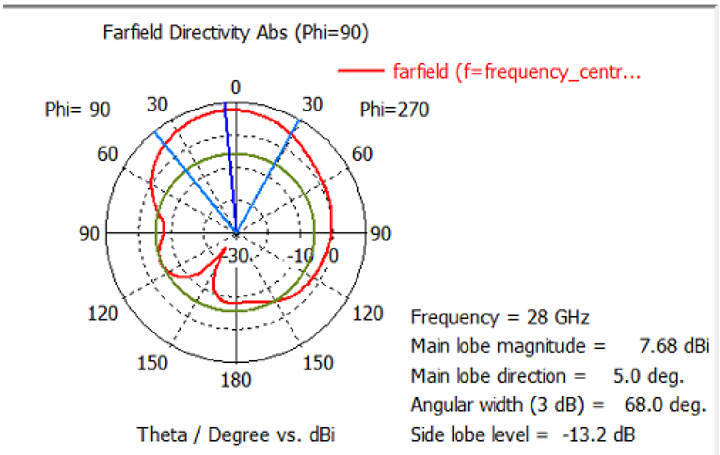


Fig. 4.29: Farfield Directivity Abs (Phi=90)

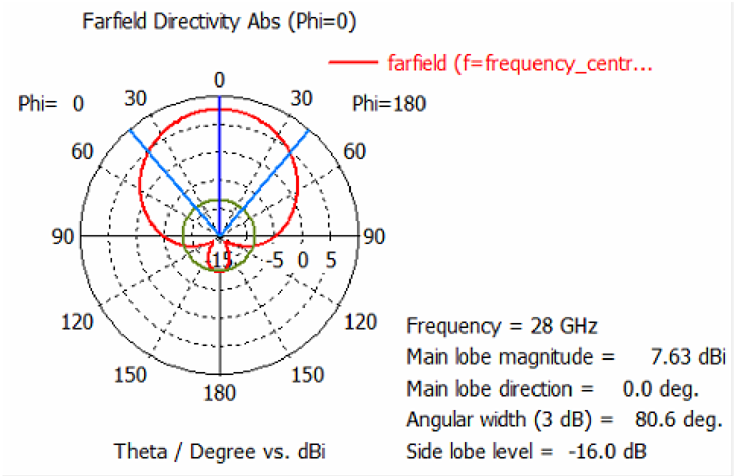


Fig. 4.30: Farfield Directivity Abs (Phi=0)

Fig. 4.30-4.32shows the combined comparison of the reflection coefficient and radiation pattern of the patch antenna. Total seven different substrate material were used including fabric, LCP, paper, PEN, PET, Polyimide and rogers 5880 and conducting materials including copper, C-Nanotubes, Nanoflake and Ag NP. It can be seen from the Fig. 4.30 that antenna designed with paper and fabric has low back lobe level then the rest of the due to that antenna with these materials has higher gain with respect to others.

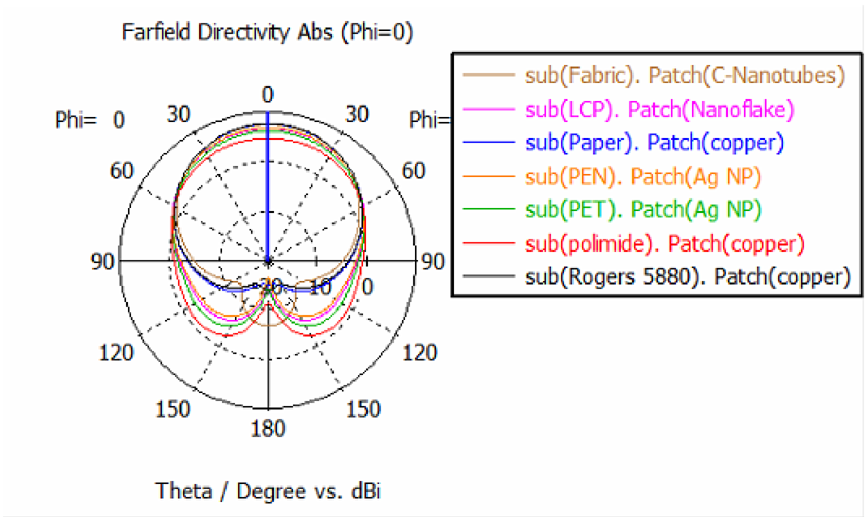


Fig. 4.31: Farfield Directivity Abs (Phi=0)

Fig. 4.32 shows the comparison of reflection coefficient of patch antenna designed on different materials. By changing the substrate materials, the S11 response deviates from the required frequency (28 Ghz) because different materials have different dielectric constant and conducting materials have different conductivity.

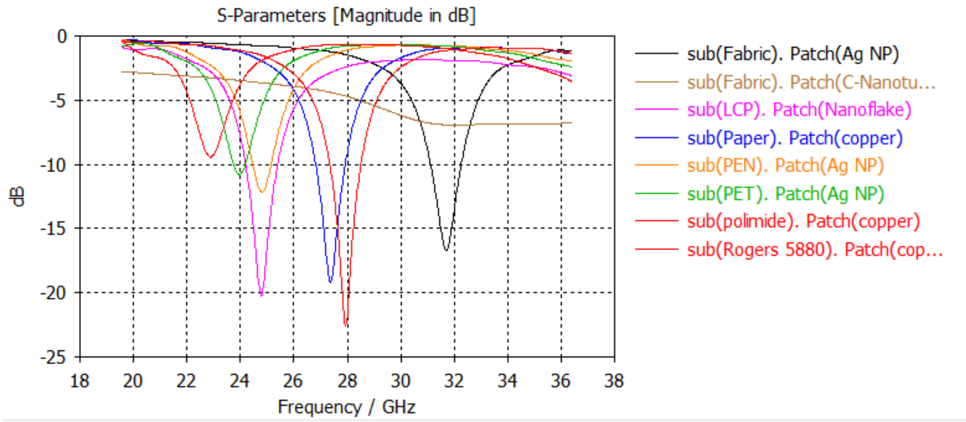


Fig. 4.32: S=Parameters [Magnitude in dB]

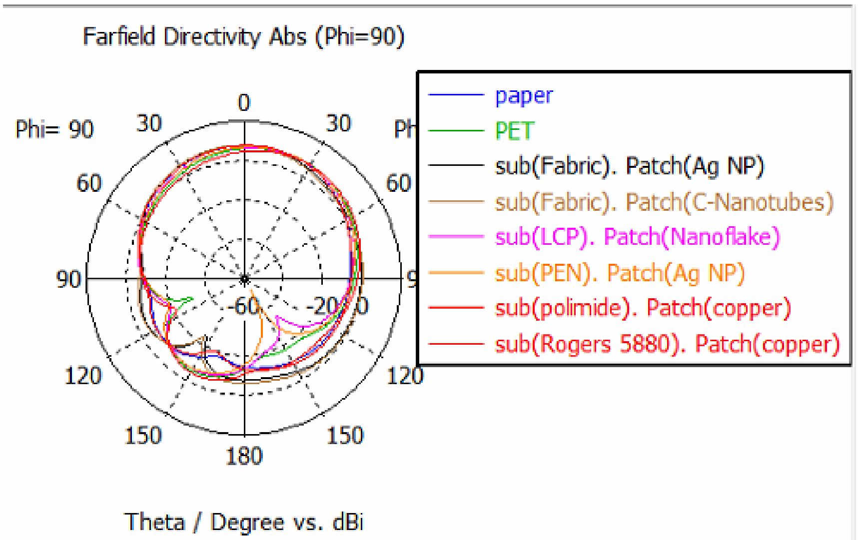


Fig. 4.33: Farfield Directivity Abs (Phi=90)

4.3 PIFA Antenna Results

PIFA antenna is and omnidirectional antenna. It is very popular in mobile industry due to its small size and omnidirectional behavior. Here PIFA antenna is design for 28 GHz (5G). In first step antenna is designed on Rogers 5880 and is matched for 28GHz. In second only substrate and conducting materials are changed in that match antenna and the changes are analyzed.

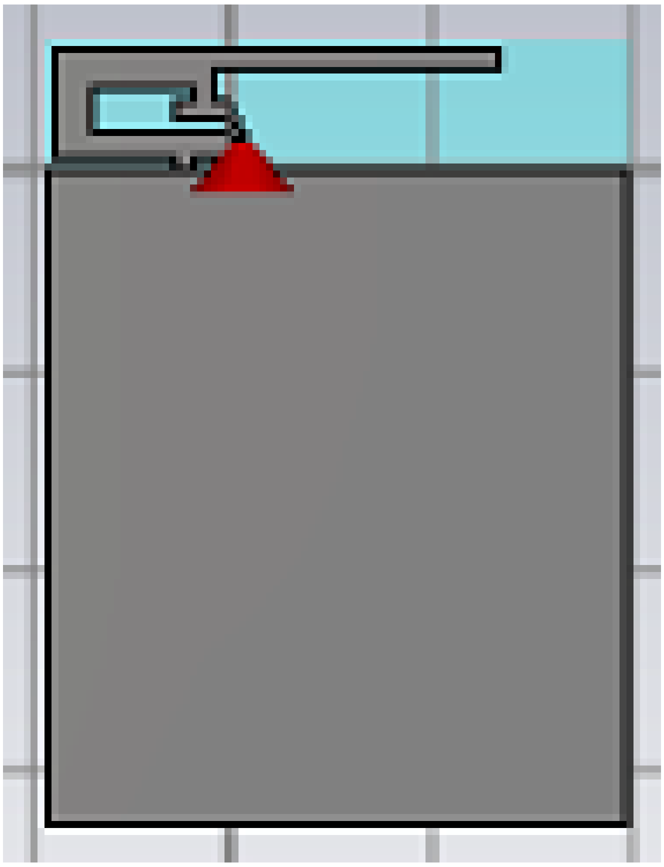


Fig. 4.37: PIFA Antenna Results

4.5.1 PIFA Antenna with Substrate FR4 and Patch Material Copper

Here the results of the PIFA antenna with FR4 and coppers is shown in Fig. bellow. S11 plot shows that antenna is well matched at 28 GHz. As the response is less then -10 dB in a band of 26.4 GHz to 29.5 GHz.

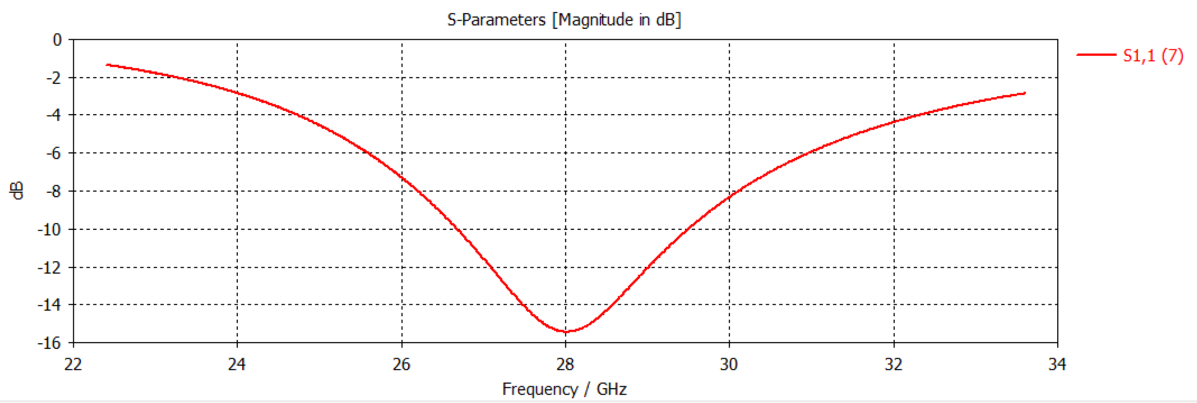


Fig. 4.38: Substrate FR4 and patch material copper

Radiation pattern of the antenna is shown below. The gain of the antenna is 2.39 dBi at 28 GHz.

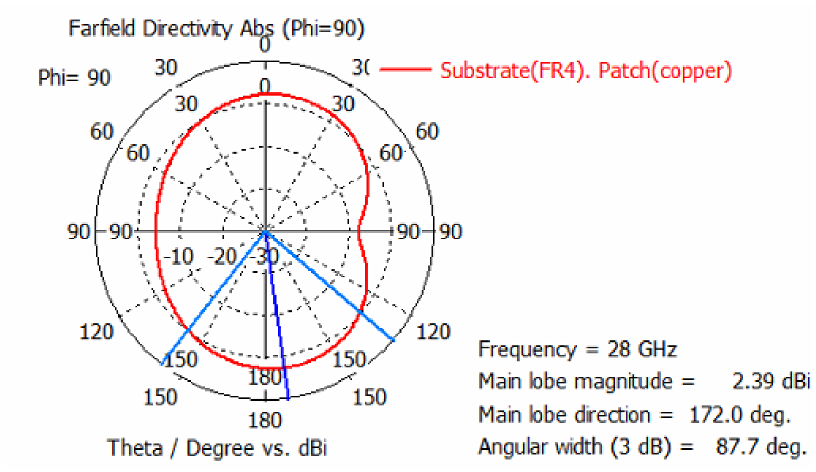


Fig. 4.39: Farfield Directivity Abs (Phi=90)

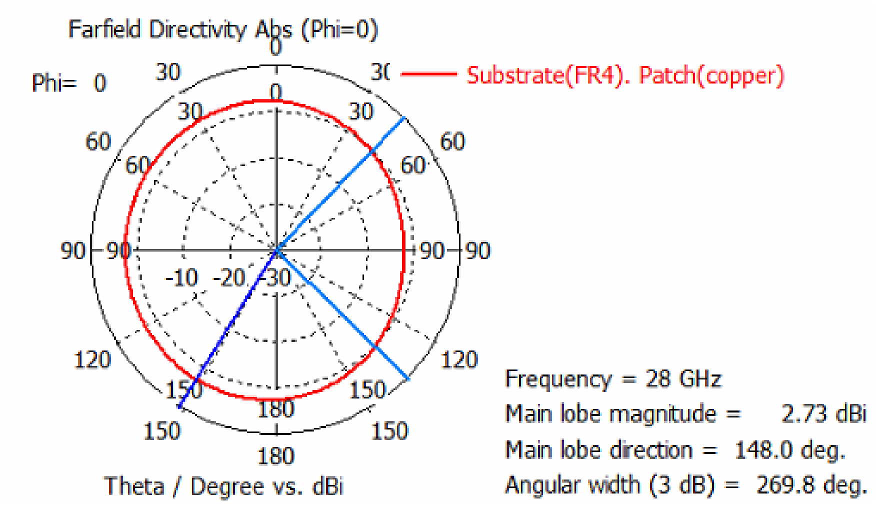


Fig. 4.40: Farfield Directivity Abs (Phi=0)

Now different materials are used to analyze the performance of the antenna. Fig. 4.30-4.32shows the combined comparison of the reflection coefficient and radiation pattern of the PIFA antenna. Total six different substrate material were used including cotton, FR4, paper, PDMS-MCT, PET and PET and conducting materials including copper, C-Nanotubes, Nanoflake and Ag NP. It can be seen from the S11 response that when antenna is designed with lower permittivity materials the response moves toward higher frequency and when designed on higher permittivity materials response moves towards lower frequency.

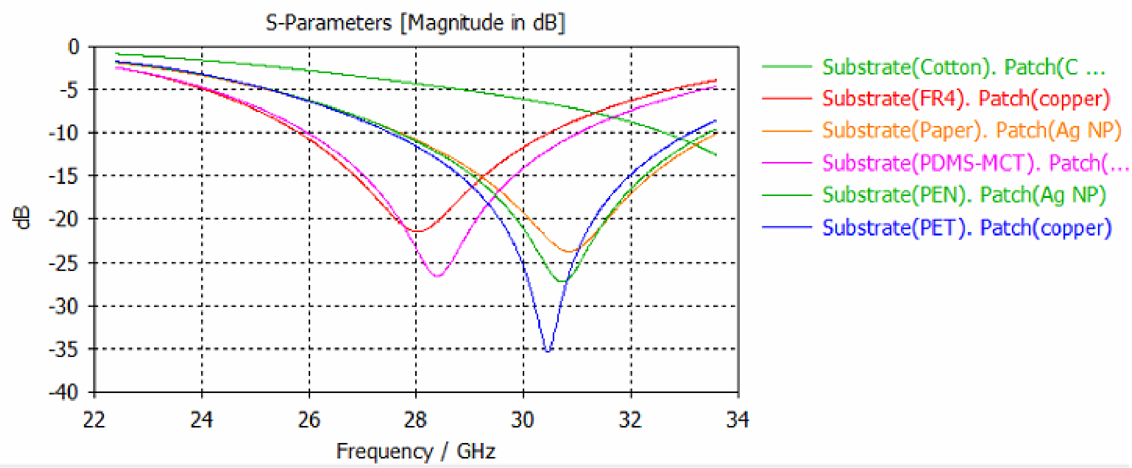


Fig. 4.59: S-Parameters [Magnitude in dB]

The pattern of PIFA antenna is unchanged which means there is no effect of material change on the radiation pattern of the antenna.

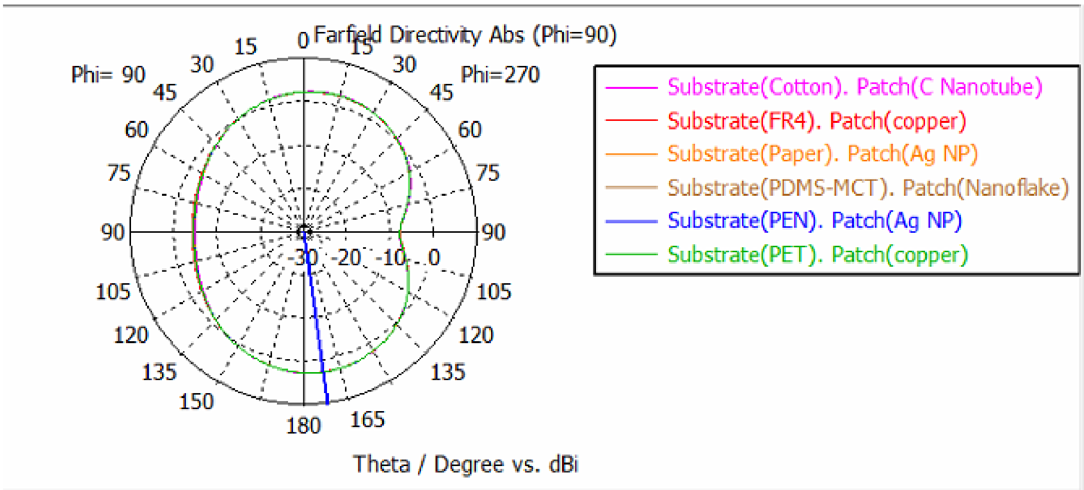


Fig. 4.60: Farfield Directivity Abs (Phi=90)

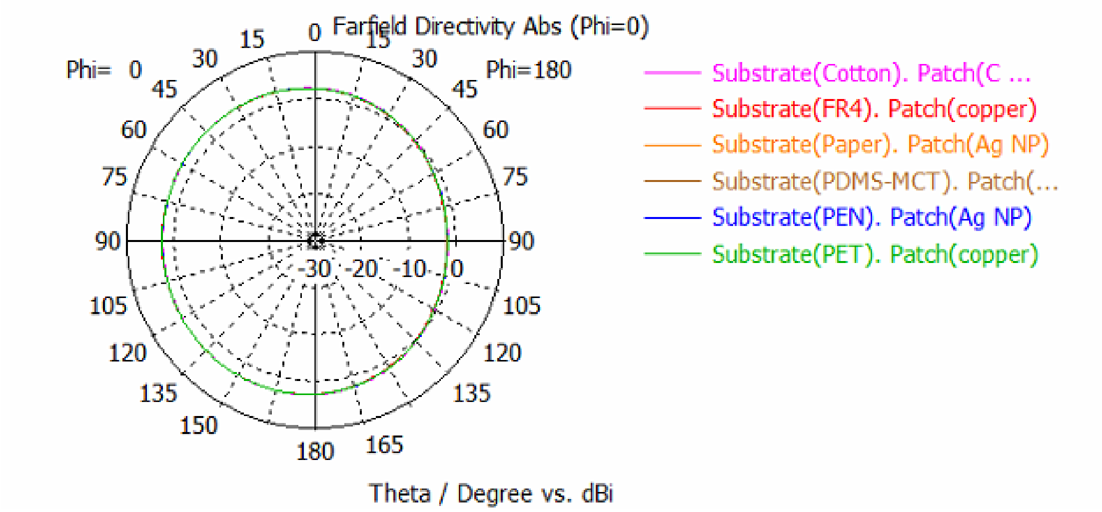


Fig. 4.61: Farfield Directivity Abs (Phi=0)

4.4 Vivaldi Antenna Results

Vivaldi antenna is a wide band antenna. This antenna is also called as planar horn. Here this antenna is designed for 5G applications. The dimensions of the antenna are given in previous section. In this section antenna is analyzed for different substrate and conducting materials as described earlier. Initially, antenna is designed on Rogers 5880 and then same antenna is analyzed for different materials. The S11 and radiation pattern of antenna designed on Rogers 5880 are given below. S11 response shows that antenna works for a large frequency band starting from 26 GHz up to 50 GHz. This shows the wide band behavior of the antenna. Radiation pattern shows that beam is focused in one direction which is along the axis of the antenna. The antenna has a high gain of 8.74 dBi at 28 GHz.

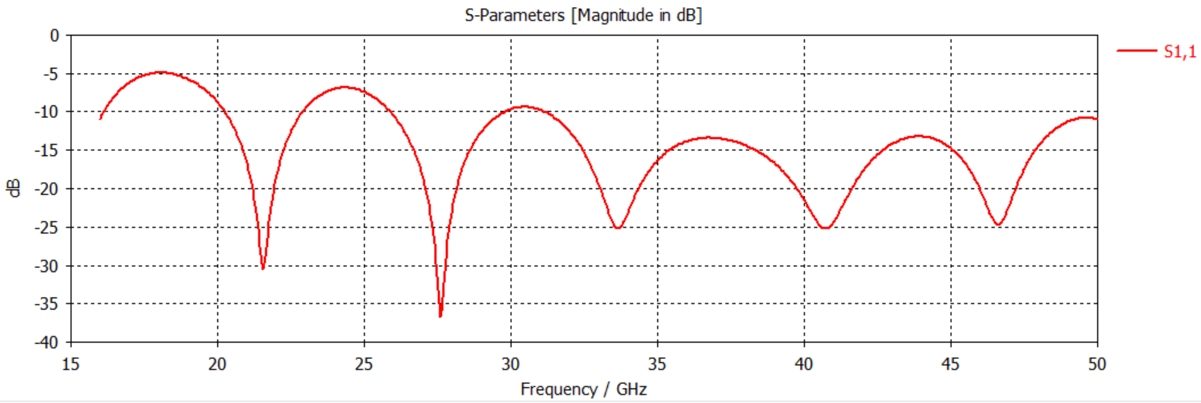


Fig. 4.63: Vivaldi Antenna Results

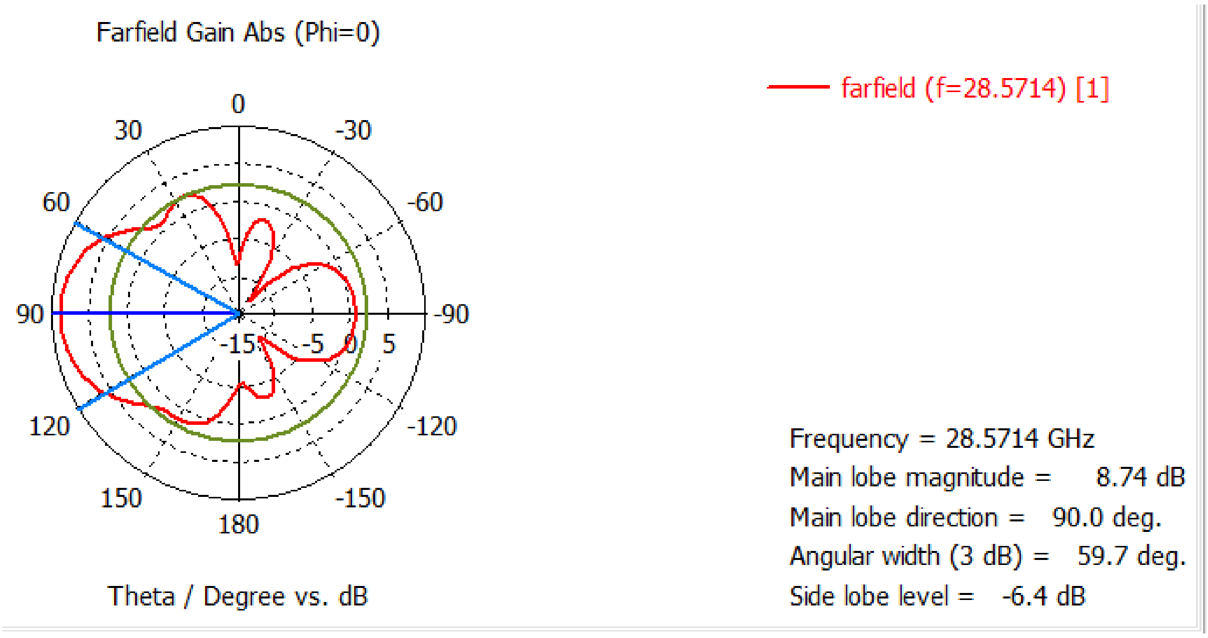


Fig. 4.64: Farfield Gain Abs (Phi=0)

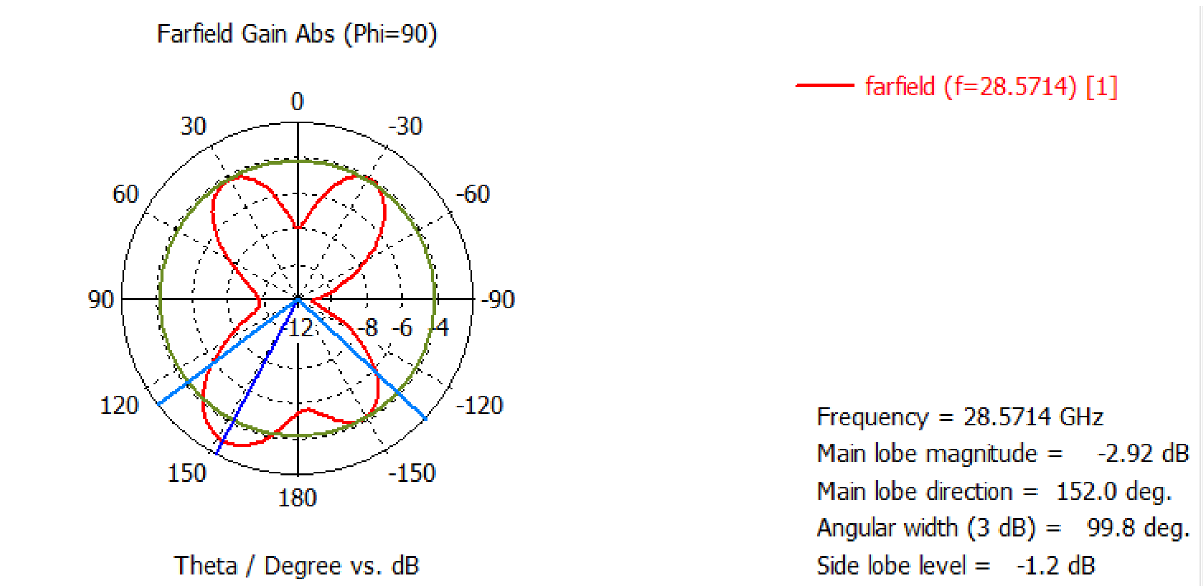
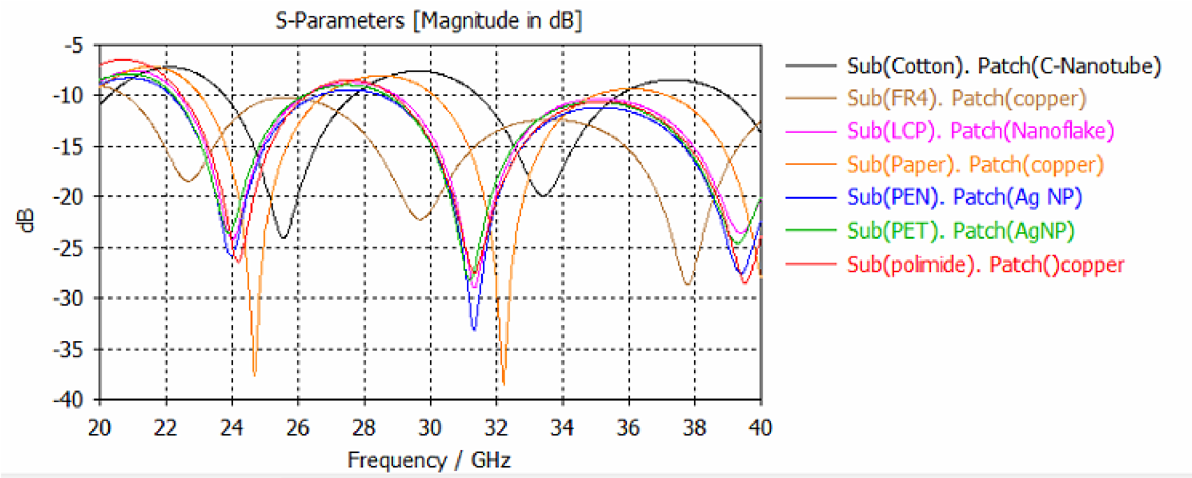
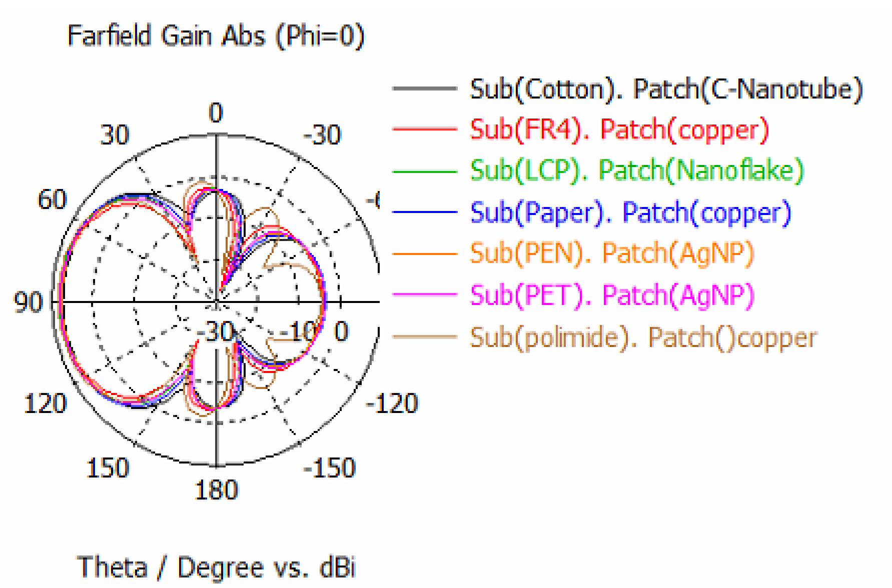


Fig. 4.65: Farfield Gain Abs (Phi=90)

Now different materials are used to analyze the performance of the Vivaldi antenna. Fig. 4.30-4.32 shows the combined comparison of the reflection coefficient and radiation pattern of the PIFA antenna. Total seven different substrate material were used including cotton, FR4, paper, PDMS-MCT, PET, polyimide and PET and conducting materials including copper, C-

Nanotubes, Nanoflake and Ag NP. It can be seen from the S11 response antenna works well for materials with higher permittivity.





Chapter 5
Conclusions & Future Work

5.1 Conclusions

As discussed, the novelty in printed antenna systems is driven by a variety of choices in materials and fabrication techniques. These novelties solve issues mainly pertaining to fabrication and usability. However, the performance of the antenna deteriorates and deviates from the technologies and materials used in the printed antenna field. As seen the results that had been simulated show the patch, where we incur a moderate change in the frequency, and it goes to a point value of 15. Now, if we consider some more results of patch antenna with substrate rogers 5880 using a patch material as a copper, the result shows a steep decline at the frequency of 28, and then the decibel increases accordingly when the frequency increases than 28. Moreover, in the results section, we can see a meaningful improvement in our results than the previous work as can be seen in detail in Chapter 4. Additionally, in the case of PIFA, we had encountered a hyperbolic curve in the frequency and the PIFA antenna results had also been improved in our research than the previous work conducted. Hence, we had discussed mainly 3 antennas in our research, which had performed very differently in terms of frequency and magnitudes.

5.2 Future Work

In the future, we would consider a bunch of antennas in our research for further analysis, and to note the change in frequency and magnitude.

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