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**Etude et conception d'une antenne**  
**reconfigurable pour des applications en ondes**  
**millimétriques**

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# Dedication

Not all letters can find the right words ...

All words cannot express gratitude, Love, respect, gratitude ...

So it's just that ...

**I dedicate this Thesis ...**

To our dear parents, for all their sacrifices, their love, their tenderness, their support and their prayers throughout our studies.

To our dear sisters ... for their constant encouragement and moral support.

To our dear brothers... for their support and encouragement.

To all our families for their support throughout our university career, May this work be the fulfillment of our so-called wishes, and the escape of our infallible support.

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## **Abstract**

*A reconfigurable antenna is an antenna in which at least one of its characteristics can be modified and controlled automatically, such as bandwidth, operational frequency, radiation pattern, and polarization. This modification is carried out by applying an external control, by adding active electrical components for RF switching such as PIN diodes. In this study, we design a radiation pattern reconfigurable antenna for millimeter-wave applications at a resonance frequency of 60GHz, using the HFSS electromagnetic simulator. Two reconfigurable antennas are achieved based on the FR-4 printed circuit technologies. These antennas are optimized by applying an extensive parametrical study. In the first proposed antenna, the direction of radiation can rotate by step angle of 90° from 0° to 360° in the azimuth plane. In the second proposed antenna, the radiation direction can rotate by a steep angle of 30° from 0° to 360° in the azimuth plane. The proposed antennas show a good radiation pattern behavior, deep  $S_{11}$ , wide bandwidth, high gain, and high efficiency.*

**Keywords:** reconfigurable antenna - PIN diode - HFSS.

## Résumé

*Une antenne reconfigurable est une antenne dans laquelle au moins une de ses caractéristiques peut être modifiée et contrôlée automatiquement, telles que la largeur de bande, la fréquence de fonctionnement, le diagramme de rayonnement ou la polarisation. Cette modification est réalisée en appliquant une commande externe, en ajoutant des composants électriques actifs pour la commutation RF tels que des diodes PIN. Dans cette étude, nous concevons une antenne avec un diagramme de rayonnement reconfigurable pour des applications au spectre des ondes millimétriques à une fréquence de résonance de 60 GHz, en utilisant le simulateur électromagnétique HFSS. Deux antennes reconfigurables sont réalisées à base de la technologie de circuits imprimés sur FR-4. Ces antennes sont optimisées en appliquant une étude paramétrique approfondie. Dans la première antenne proposée, la direction de diagramme de rayonnement peut tourner avec un pas de 90 °, de 0 ° à 360 ° dans le plan azimutal. Dans la deuxième antenne proposée, la direction de diagramme de rayonnement peut tourner avec un pas de 30 °, de 0 ° à 360 ° dans le plan azimutal. Les deux antennes proposées présentent un bon comportement de diagramme de rayonnement, un  $S_{11}$  profond, une large bande passante, un gain élevé et un rendement élevé.*

**Mots clés:** antenne reconfigurable - diode PIN - HFSS.

## ملخص

الهوائي القابل للضبط هو هوائي يمكن تعديل واحدة من خصائصه على الأقل والتحكم فيها تلقائيًا، مثل عرض النطاق الترددي، التردد التشغيلي، الإشعاع، والاستقطاب. يتم إجراء هذا التعديل من خلال تطبيق تحكم خارجي، عن طريق إضافة مكونات كهربائية نشطة لتبديل التردد اللاسلكي مثل صمامات PIN الثنائية. في هذه الدراسة، قمنا بتصميم هوائي قابل للضبط والتحكم في اتجاه الإشعاع والذي يعمل في مجال ترددات الموجات المليمترية وبتردد رنين يساوي 60 جيجاهرتز وذلك باستخدام برنامج محاكاة HFSS. تم الحصول على هوائيين قابلين للضبط بناءً على تقنيات الدوائر المطبوعة FR-4. تم تحسين هذه الهوائيات من خلال تطبيق دراسة بارامترية واسعة النطاق. في أول هوائي مقترح، يمكن أن يدور اتجاه الإشعاع بزاوية 90 درجة من 0 إلى 360 درجة في مستوى السم. في الهوائي الثاني المقترح، يمكن أن يدور إشعاع الاتجاه بزاوية خطوة مقدارها 30 درجة من 0 درجة إلى 360 درجة في مستوى السم. يُظهر الهوائي المقترح سلوكًا جيدًا لمخطط الإشعاع، وعمق  $S_{11}$ ، وعرض نطاق عريض، وكسب مرتفع، وكفاءة عالية.

**الكلمات المفتاحية:** هوائي قابل للضبط -صمام ثنائي PIN - HFSS.

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## **List of Abbreviations**

**HFSS:** High-Frequency Structure Simulator

**PIN:** Positive Intrinsic Negative Diode.

**MEMS:** Micro Electro Mechanical System

**WLAN:** Wireless Local Area Network

**IEEE:** Institute of Electrical and Electronics Engineers

**MGWS:** Multiple Gigabit Wireless System

**LAN:** local area network

**UHD:** Ultra-high-definition

**PCB:** printed circuit board

**RFID:** Radio-Frequency Identification

**GPS:** Global Positioning System

**MIMO:** Multiple-Input and Multiple-Output

**TEM:** Transverse Electric-Magnetic

**RHCP:** Right-Hand Circular Polarization

**LHCP:** Left-Hand Circular Polarization

**FETs:** Field-Effect Transistors

**VSWR:** Voltage Standing Wave Ratio

# **GENERAL INTRODUCTION**

## General Introduction

The fifth generation of communications is expected to provide high data transfer, on the order of Gbps, improve the quality of services provided to a large number of users in response, and meeting the increasing demands on audio, video, and multimedia applications. In order to meet this increasing demand for higher transmission rates, work has been done to improve the signal-to-noise ratio in wireless communication channels and increase the available field width. Therefore, recently attention has been paid to the use of modulated antennas. Many studies have been completed on the modular antenna based on the chip antenna, and the methods of selecting the working frequency and the polarization of the antenna [1].

Reconfigurability can be used through many methods; including changing the physical dimensions of the antenna, through a change in the antenna feeding network or a change in the radiation segment of the antenna or the ground segment, as these changes lead to a change in the electrical current distribution on the antenna surface [2-3].

Since formability changes the features and specifications of the antenna, there are several methods to control the form of the antenna, including mechanical and optical photo-conducting switches and electronic RF switching devices. In this method, both RF PIN diodes and RF MEMS are considered ideal equipment to use in the antenna reconfiguration process as these tools require less complex circuits than other lower cost methods. Thus, they have been widely used in many studies and researches [4].

Ideally, reconfigurable antennas should be able to change their operating frequency, polarization, and radiation pattern independently to meet varying operating requirements. Moreover, the development of these antennas faces significant challenges to both antenna modeling and system designer. However, these challenges will come not only from the antenna design but also the surrounding technologies that enable reconfigurability [5].

Recently, theoretical and measurement results of 5G communications operating at mm-Wave were extensively studied. The researchers presented and designed the unprecedented hardware challenges and essential design considerations concerned with the antenna system methodology for future communications. The designed antenna provides a good and useful isotropic radiated power with minimum losses for practical use in 5G cellular communications [6]. Thus, one of the efficient methods to overcoming these challenges is to design reconfigurable radiation pattern antennas. These antennas can diversify the direction of the main lobe or cancel it at specific direction angles. Besides, it provides a wider coverage area with less interference and noise signals by controlling the main beam locations.

Practically, a reconfigurable antenna is an antenna in which at least one of its characteristics can be modified after manufacture (bandwidth, operational frequency, radiation pattern and polarization). This modification is carried out by applying an external control, by adding active electrical components (the PIN diode, Varactors, RF-MEMS) of

optical types like photoconductors or a physical type such as the geometric modification of the shape of the antenna. We can classify the reconfigurable antennas in four categories: reconfigurability in frequency, radiation, in polarization, or a combination of two or more reconfigurations of previously indicated characteristics [7]. Thus, reconfigurable antennas are considered very efficient in terms of their performance, flexibility, and efficient use of the frequency spectrum [8].

In our study, we will design a radiation pattern reconfigurable antenna for millimeter-wave applications and 60GHz spectrum, using HFSS electromagnetic simulator. To better understand the context of the planned study, we draw up, in the first chapter, a state of the art of millimeter waves characteristic and applications, reconfigurable antennas as well as their types in frequency, radiation, and polarization. Their advantages and disadvantages are also highlighted in addition to their techniques and the main concepts used.

The second chapter include a parametric study of a dedicated antenna to show the effect of the various physical and electrical parameters on the characteristics of this antenna, geometry optimization, and the steps we've applied to get the final shape of our reconfigurable antenna.

The third chapter include the obtained results from simulation on HFSS with the discussion about the radiation pattern, gain, impedance, VSWR and the efficiency of the antenna.

Finally, we finish this study with a general conclusion.

# *CHAPTER I*

# **RECONFIGURABLE ANTENNAS**

## **I.1 Introduction**

With current technological development and the emergence of new wireless applications, the frequency resources available are limited and the powers are regulated for security reasons. Innovative solutions must be put in place to increase transmission performance in terms of speed and efficiency; among these, reconfigurable antennas are the subject of much research and become a very important imperative in many wireless communications.

In this chapter, we will go through some basics of reconfigurable antennas and its challenges in the millimeter waves.

## **I.2 Millimeter Waves (mmWave)**

Communication systems have attracted significant interest regarding meeting the capacity requirements of the future 5G network. The mmWave systems have frequency ranges between 30 and 300 GHz where a total of around 250 GHz bandwidths are available. However, the available bandwidth of mmWave frequencies exhibits many challenges; the propagation characteristics are significantly different from microwave frequency bands in terms of path loss, diffraction and blockage, rain attenuation, atmospheric absorption, and foliage loss behaviours [9].

In general, the overall loss of mm-Wave systems is significantly larger than that of microwave systems for a point-to-point link. Fortunately, however, the small wavelengths of mm-Wave frequencies enable large numbers of antenna elements to be deployed in the same form factor thereby providing high spatial processing gains that can theoretically compensate for at least the isotropic path loss. Nevertheless, as mm-Wave systems are equipped with several antennas, several computations and implementation challenges arise to maintain the anticipated performance gain of mm-Wave systems [9].

### **I.2.1 Millimeter-Wave Characteristic and Propagation**

Millimeter-wave (mmWave) cellular systems, that operate in the 30-300 GHz band, seems to be an auspicious candidate for next-generation 5G cellular system, which is expected to support data rates of multiple Gb/s. However, employing mmWave requires dealing with the propagation attributes and the channel impairments of the high-frequency bands. Major impediments of mmWave propagation are higher path loss due to higher carrier frequency; reduced scattering which in turn reduces the available diversity, and increased effect of blockage as a result of weaker non-line-of-sight paths. Besides, the effect of noise power is more pronounced due to the usage of larger bandwidths [10].

### **I.2.2 Millimeter-Wave Applications**

#### **I.2.2.1 5G and Small Cell Concept**

5G is one of the most discussed technologies in recent times. Due to its requirement to support a higher data rate, 5G will be using millimeter waves (between 24GHz and 86 GHz range). Tech companies are testing and investing in WLAN infrastructure with the support of

millimeter waves. Small cells concept could choose millimeter waves in its future implementation. Millimeter-waves can replace traditional optical fiber transmission lines connecting mobile base stations [11].

### **I.2.2.2 V Band**

The V band ("vee-band") is a standard designation by the Institute of Electrical and Electronics Engineers (IEEE) for a band of frequencies in the microwave portion of the electromagnetic spectrum ranging from 40 to 75 gigahertz (GHz). The V band is not heavily used, except for millimeter-wave radar research and other kinds of scientific research. It should not be confused with the 600–1000 MHz range of Band V (Band Five) of the UHF frequency range. [11]

The V band is also used for high capacity terrestrial millimeter wave communications systems. In the United States, the Federal Communications Commission has allocated the frequency band from 57 to 71 GHz for unlicensed wireless systems. These systems are primarily used for high capacity, short distance (less than 1 mile) communications. Besides, frequencies at 70, 80, and 90 GHz have been allocated as "lightly licensed" bands for multi-gigabit wireless communications. All communications links in the V band require an unobstructed line of sight between the transmitting and receiving point, and rain fade must be taken into account when performing link budget analysis. [12]

### **I.2.2.3 Wi Gig**

WiGig, alternatively known as 60GHz Wi-Fi, refers to a set of 60 GHz wireless network protocols. It includes the current IEEE 802.11ad standard and also the upcoming IEEE 802.11ay standard.

The WiGig specification allows devices to communicate without wires at multi-gigabit speeds. It enables high-performance wireless data, display and audio applications that supplement the capabilities of previous wireless LAN devices. WiGig tri-band enabled devices, which operate in the 2.4, 5 and 60 GHz bands, deliver data transfer rates up to 7 Gbit/s (for 11ad), about as fast as an 8-band 802.11ac transmission, and more than 11 times faster than the highest 802.11n rate, while maintaining compatibility with existing Wi-Fi devices. The 60 GHz millimeter wave signal cannot typically penetrate walls but can propagate off reflections from walls, ceilings, floors, and objects using beamforming built into the WiGig system. When roaming away from the main room, the protocol can switch to make use of the other lower bands at a much lower rate, both of which can propagate through walls.

The name WiGig comes from Wireless Gigabit Alliance, the original association being formed to promote the adaption of IEEE 802.11ad, however, WiFi Alliance now certifies it [13].

### **I.2.2.4 Satellite Communication**

Millimeter waves are perfect candidates for satellite communication. At higher altitudes of orbits, it operates perfectly with massive data rate and low latency [11.]

### **I.2.3 Reconfigurable Antennas for Millimeter-Wave Communication**

Communication between 30 and 300 GHz is defined as communication over millimeter-wave frequencies. The mm-Wave spectrum has become of high interest for many system designers for its many benefits that are mainly focused on its wide bandwidths. Such wide bandwidths are useful and practical when it comes to high-speed data transmission and video distribution. The propagation characteristics of mm-Waves are very particular in the sense that mm-Wave signals can only travel a few miles or less. These waves do not penetrate solid materials very well and are heavily affected by environmental factors such as raindrops and fog [14].

### **I.2.4 Advantages and Disadvantages of Millimeter Waves**

- **Advantages**

- ⇒ Millimeter waves can support higher data rates due to higher bandwidth.
- ⇒ Millimeter waves don't need fiber optic cable installation to achieve high data rate, contrary to conventional higher data rate transmission.
- ⇒ Conventional higher data rate transmission has difficulties for implementation, maintenance and it is not economical.
- ⇒ Any damage to the fragile fiber strand could cause full disruption of the transmission system, which not the case in millimeter-wave.
- ⇒ Millimeter-wave technology can easily achieve 10 GBps data rate for communication.
- ⇒ Another major advantage of millimeter wave technology is its tiny component size. Modern smart devices and mobile phones have to be efficient and small in size. Millimeter waves are complex and it enables high-security transmission [11].

- **Disadvantages**

- ⇒ Millimeter waves require line of sight communication.
- ⇒ It is not suitable for long-distance communication. Millimeter-wave architecture requires advanced technology infrastructure to develop a system
- ⇒ One of the major disadvantages of the millimeter waves is the distortion caused by the atmosphere. This phenomenon can be observed in digital video broadcasting (DVB services). During the cloudy atmosphere, DVB services will be distorted due to poor signal quality [11].

### **I.3 60GHz Spectrum**

IEEE 802.11ad is an amendment to the IEEE 802.11 wireless networking standard, developed to provide a Multiple Gigabit Wireless System (MGWS) standard at 60 GHz frequency, and is a networking standard for WiGig networks. Because it uses the V band of millimeter-wave frequency, the range of IEEE 802.11ad communication would be rather limited (just a few meters and difficult to pass through obstacles/walls) compared to other conventional Wi-Fi systems. However, the high frequency allows it to use more bandwidth which in turn enables the transmission of data at high data rates up to multiple gigabits per

second, enabling usage scenarios like transmission of uncompressed UHD video over the wireless network [15].

## **I.4 Microstrip Antenna:**

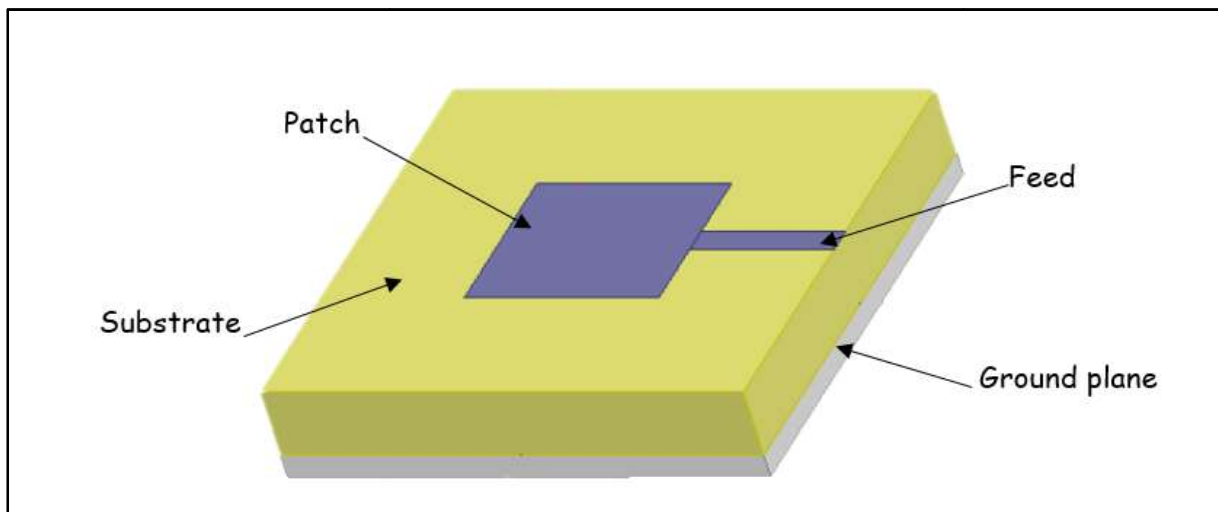
### **I.4.1 Definition**

Microstrip antenna was first introduced in the 1950s. However, this concept had to wait for about 20 years to be realized after the development of the printed circuit board (PCB) technology in the 1970s [16].

Since then, Microstrip antennas are the most common types of antennas with a wide range of applications due to their apparent advantages of lightweight, low profile, low cost, planar configuration, easy of conformal, superior portability, suitable for arrays with the ease of fabrication and integration with microwave monolithic integrate circuits (MMICs)[16].

They have been widely engaged for the civilian and military applications such as radio-frequency identification (RFID), broadcast radio, mobile systems, global positioning system (GPS), television, multiple-input multiple-output (MIMO) systems, vehicle collision avoidance system, satellite communications, surveillance systems, direction founding, radar systems, remote sensing, missile guidance, and so on[16].

Antenna is a transducer, which transmits or receives electromagnetic waves. Microstrip antennas have several advantages over conventional microwave antenna and therefore are used in a variety of practical applications. Microstrip antenna in its simplest design is shown in Figure 1. It consists of a radiating patch on one side of the dielectric substrate ( $\epsilon_r \leq 10$ ) and a ground plane on the other side [16].



**Figure I.1:** *Microstrip antenna geometry.*

### **I.4.2 Rectangular Patch Antenna**

The rectangular patch is by far the most widely used configuration. It is very easy to analyze using both the transmission-line and cavity models, which are most accurate for thin substrates [17].

The basic steps for the development of rectangular patch antenna (RPA) are:

- **Step 1:** A parameter width of the radiating RPA is calculated from this equation:

$$W = \frac{c}{2f} \sqrt{\frac{2}{\epsilon_r + 1}} \quad (I.1)$$

where:

c: velocity of light,  $3 \times 10^8$  m/s.

$\epsilon_r$ : dielectric constant of the substrate.

f: resonant frequency of the antenna.

- **Step 2:** Effective dielectric constant of the PRA is determined as:

$$\epsilon_r = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2} \times \left(1 + \frac{12 \times h}{w}\right) - \frac{1}{2} \quad (I.2)$$

- **Step 3:** The effective length is specified at the resonance frequency

$$L_{\text{eff}} = \frac{c}{2f_r \sqrt{\epsilon_{\text{eff}}}} \quad (I.3)$$

- **Step 4:** Extension length of the PRA computed with this equation:

$$\Delta L = 0.412 \times h \times \frac{(\epsilon_{\text{eff}} + 0.3) \left(\frac{w}{h} + 0.264\right)}{(\epsilon_{\text{eff}} - 0.258) \left(\frac{w}{h} + 0.8\right)} \quad (I.4)$$

The length "L" of the PRA is calculated as:

$$L = L_{\text{eff}} - 2\Delta L \quad (I.5)$$

### I.4.3 Transmission Line Model for analysis of Microstrip Patch Antenna

This model represents the microstrip antenna by two slots of width 'w' and height 'h', separated by a transmission line of length 'L' [18].

The microstrip is essentially a nonhomogeneous line of two dielectrics, typically substrate and air. Most of the electric field lines reside in the substrate and parts of some lines in the air [18]. As a result, this transmission line cannot support pure transverse electric-magnetic (TEM) mode of transmission, since phase velocities would be different in the air and the substrate. Instead, the dominant mode of propagation would be the quasi-TEM mode. Hence an effective dielectric constant ( $\epsilon_{\text{reff}}$ ) must be obtained in order to account for the fringing and the wave propagation in the line. The value of  $\epsilon_{\text{reff}}$  is slightly less than  $\epsilon_r$  because the fringing fields around the periphery of the patch are not confined in the dielectric substrate but are also spreads in the air [18].

The expression for  $\epsilon_{\text{reff}}$  is given by

$$\epsilon_{\text{reff}} = \frac{\epsilon_{\text{reff}} + 1}{2} + \frac{\epsilon_{\text{reff}} - 1}{2} * \left(1 + \frac{12 \times h}{w}\right) - \frac{1}{2} \dots \dots \dots (I.6)$$

Where  $\epsilon_{\text{reff}}$  = Effective dielectric constant

$\epsilon_r$  = Dielectric constant of substrate

$h$  = Height of the dielectric substrate

$w$  = Width of the patch

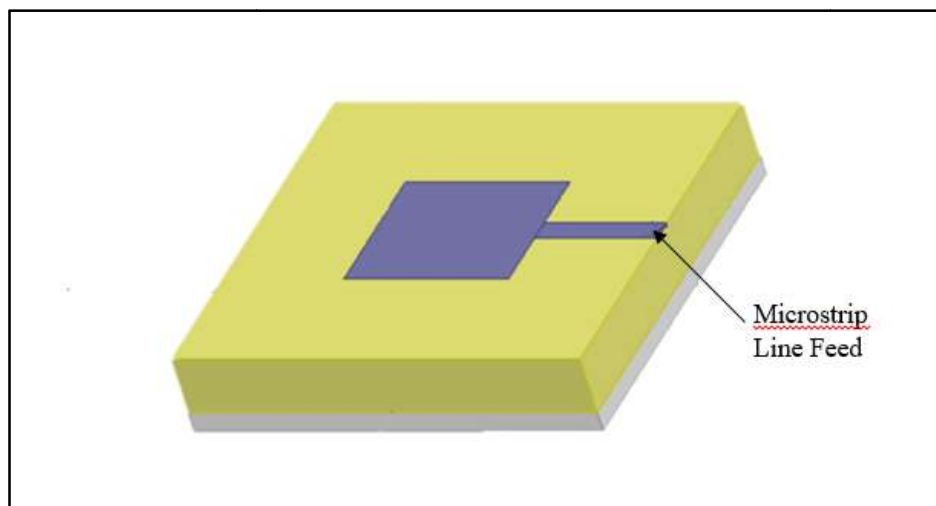
### **I.4.2 Feeding Techniques**

Different methods are available to feed microstrip patch antennas. These methods can be contacting and non-contacting methods. In the contacting method, the RF power is fed directly to the radiating patch using a connecting element such as a microstrip line.

In the non-contacting method, power is transferred between the microstrip line and the radiating patch through electromagnetic coupling. There are many feed techniques but the four most popular feeding techniques used are microstrip line, coaxial probe (both contacting schemes), aperture coupling, and proximity coupling (both non-contacting schemes)[19].

#### **I.4.2.1 Microstrip Line Feed**

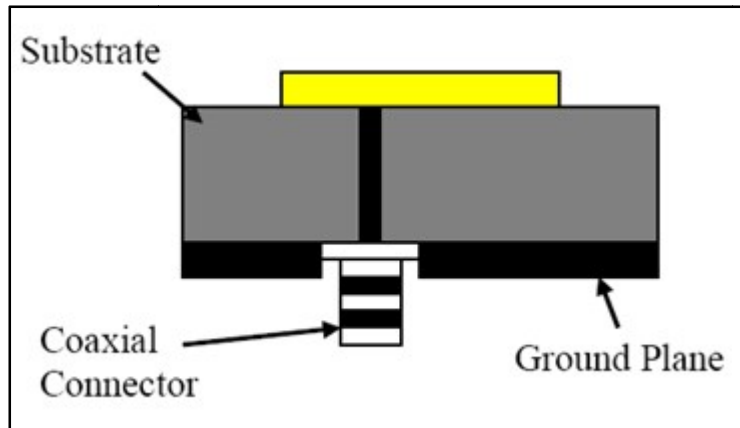
In this kind of feeding process (Fig I.2), the edge of the microstrip patch is connected directly to a conducting strip. This feeding method offers the benefit that the conducting line can have the opportunity of engraved on the same substrate of patch antenna providing a planar shape. The width of the conducting element is smaller as compared to the patch antenna. [17]



**Figure I.2:** *Microstrip Line Feed.*

#### **I.4.2.2 Coaxial Feed**

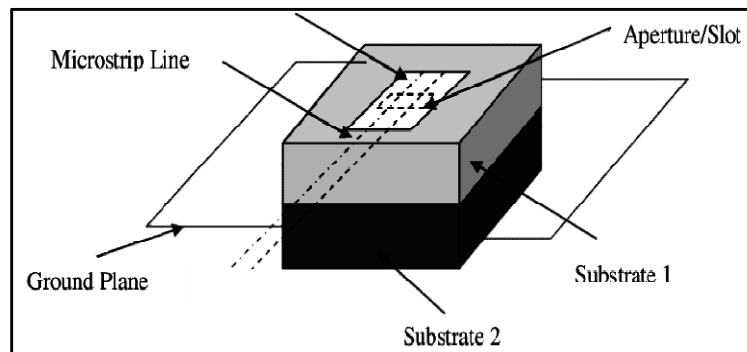
In this configuration, the inner conductor of the coaxial connector extends throughout the dielectric and is soldered to the radiating patch, while the outer conductor is coupled to the ground plane. The major advantage of this type of feeding is that the feed can be placed at any of the desired 26 locations inside the patch in order to match with its input impedance. The disadvantage is that it provides a narrow bandwidth and is complex to model [19].



**Figure I.3:** Coaxial Feed [20].

#### I.4.2.3 Aperture Coupled Feed

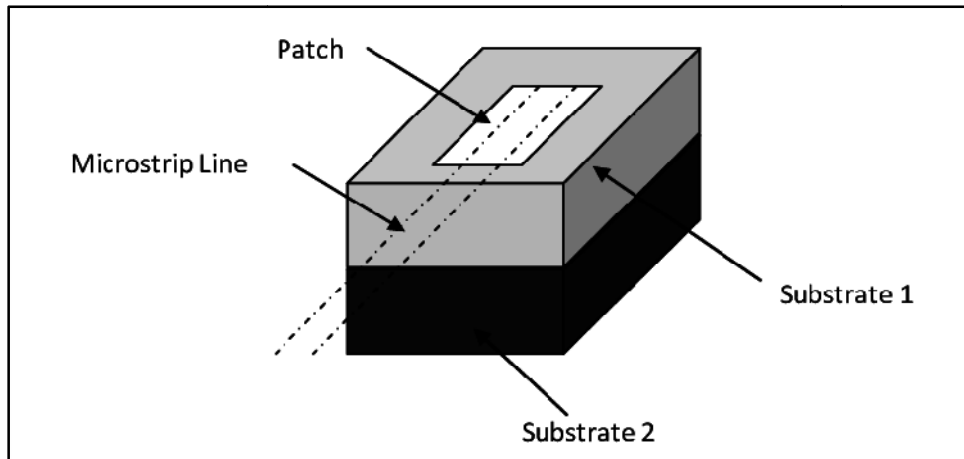
In this technique, the radiating patch and the microstrip feed line are separated by the ground plane. The patch and the feed line is coupled through a slot in the ground plane. The coupling slot is centered below the patch, leading to low cross-polarization due to the symmetry of the configuration. Since the ground plane separates the patch and the feed line, spurious radiation is minimized. The main disadvantage of this feed technique is that it is difficult to fabricate due to multiple layers, which also increases the antenna thickness [19].



**Figure I.4:** Aperture Coupled Feed[21].

#### I.4.2.4 Proximity Coupled Feed

This type of feed technique is also called as the electromagnetic coupling scheme. Two dielectric substrates are used and the feed line is between the two substrates. The radiating patch is on top of the upper substrate. The main advantage of this feed technique is that it eliminates spurious feed radiation and provides very high bandwidth (as high as 13%). The major disadvantage of this feed scheme is that it is difficult to fabricate because of the two dielectric layers which need proper alignment [19].



**Figure I.5:** *Proximity Coupled Feed [22].*

## **I.5 Reconfigurable Antenna**

### **I.5.1 Definition**

Reconfigurable antenna term was first introduced in 1998 [23]. An antenna is said to be reconfigurable (or agile) if it is able to dynamically modify its functionality after its manufacture, that is to say, to modify one or more of its operating characteristics (in terms of frequency, polarization, or diagram depending on the needs dictated by the antenna environment and the needs of the application. [24]

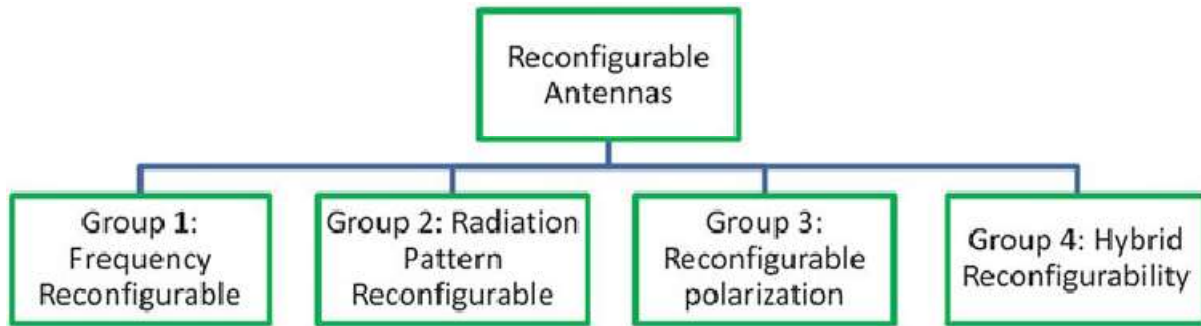
The reconfiguration of the antenna is carried out by modifying the distribution of electric current, consequently, the properties of the field electromagnetic and impedance, thus the properties of emission and reception [25], and this can be in a discrete or continuous way.

### **I.5.2 Reconfigurability Performance**

The reconfiguration of the antenna can be obtained by various approaches. Some techniques use active localized components which make it possible to modify the current lines or the impedance in a quasi-punctual manner; others rely on a mechanical alteration of the structure constituting the antenna, while others use substrates with tunable characteristics. Other approaches are based on the reconfigurability of the power supply networks, or even appropriately excite the antenna networks [26].

### **I.5.3 Classification of Reconfigurable Antennas**

Based on the operational properties dynamically adjusted, e.g. frequency of operation, radiation pattern, polarization or a combination of any of these properties, reconfigurable antennas can be classified as follows: [27]



*Figure I-6: classification of reconfigurable antennas [27].*

### **I.5.3.1 Frequency Reconfigurable Antennas:**

These antennas can be developed by two mechanisms: electrical or mechanical. The electrical mechanism employs discrete tuning and continuous tuning methods. Discrete tuning can be achieved by radio frequency (RF) switches and continuous tuning can be achieved by varactor diodes. The mechanical mechanism employs the impedance loading tunable materials such as liquid crystals, metasurface to achieve the frequency reconfiguration [27].

### **I.5.3.2 Pattern Reconfigurable Antennas:**

These antennas use movable/rotatable structures like metasurface or including switchable in reactively loaded capacitive elements for the intentional modification of the spherical distribution of radiation pattern [27].

### **I.5.3.3 Polarization Reconfigurable Antennas:**

These antennas use switching between different polarizations, i.e. from linear polarization to left-hand circular polarization (LHCP) and right-hand circular polarization (RHCP), using multi modes structure or metasurface. To reduce the polarization mismatch, losses in portable devices, switching between horizontal, vertical and circular polarizations are needed [27].

### **I.5.3.4 Compound Reconfigurable Antennas:**

These antennas use the simultaneous tuning of several antenna parameters, e.g. frequency and radiation pattern, for independent reconfiguration of operating frequency, radiation pattern and polarization, via a parasitic pixel layer [27].

## **I.5.3 Radiation Characteristics**

Radiation pattern is one of the most important characteristics of antennas. It is a graphical representation of an antenna's far-field radiation properties. It also describes the ability of an antenna to transmit/receive signals in a direction. It can be specified by the unit decibels (dB).

Polarization of an antenna's radiation pattern can be defined as the change in the electric field vector with respect to the direction of propagation. Polarization is an important parameter in an antenna. It acts as a filter for undesired signals. There are three types of polarizations which are linear, elliptical, and circular polarization [28]. In the case of polarization, the antenna radiation pattern describes the fundamental shape and characteristics of the antenna.

Beamwidth is one of the parameters which can be described in a two-dimensional plane in the radiating volume of the antenna. The half-power beamwidth of the antenna can be defined as the parameter which measures the angle surrounding the direction of maximum radiation. It describes the antenna’s normalized radiation intensity is greater than 0.5 [29].

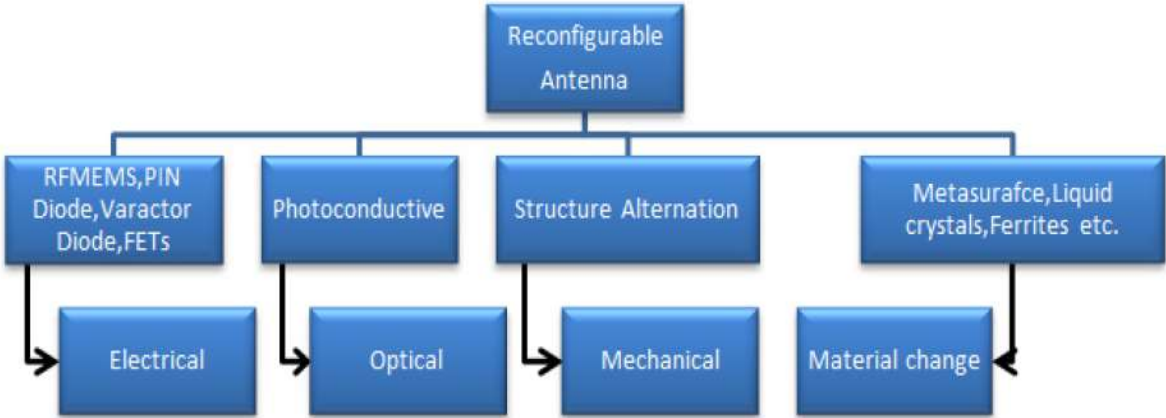
The first null beam width can be defined as it is the angle between the first pattern nulls adjacent to the main lobe of the pattern. The two parameters which are half-power beamwidth and full-null beam width describe the shape and the extent of the main beam of the antenna.

Directivity and gain describe the antenna efficiency. The antenna’s directivity can be defined as the ratio of the radiation intensity in a given direction to the average radiation intensity in overall direction. Gain can be defined as the ratio of the radiation intensity of a test antenna in a given direction, to the radiation intensity of an isotropic antenna.

If a direction is not particularly specified for directivity or gain, the direction of the maximum radiation intensity is implied which describes the loss as the loss does not arise from the impedance and polarization mismatch. If the antenna is ideal and there is no power dissipation, then the gain and directivity of an antenna can be interchanged [29].

**I.3.4 Reconfiguration Techniques**

Based on the requirement on the reconfiguration property of the antenna, there are four major types of reconfiguration techniques: electrical, optical, mechanical and material [30]-[31].The reconfiguration techniques are presented in Figure I-7.



*Figure I-7. Antenna reconfiguration techniques [30]*

Electrical reconfiguration techniques are based on the use of switches to connect or disconnect antenna parts and redistribute the currents by altering the radiated fields of the antenna’s effective aperture [32]-[33].

Radio-frequency micro-electromechanical systems (RF-MEMS), PIN diodes, varactor diodes, or field-effect transistors (FETs) are integrated into the antenna to redirect their source currents.

RF-MEMS switches based antennas rely on the mechanical movement of the switches to achieve reconfiguration. Many antenna designs have resorted to RF-MEMS to reconfigure

their performance The switching speed of RF-MEMS switches is in the range of 1-200  $\mu\text{sec}$  which is low for some applications. [27]

PIN diodes and varactor diodes have faster-switching speed as compared to RF-MEMS switches and are in the range of 1-100 nsec [26]. Reconfigurable antennas using PIN diodes have more dynamic reconfiguration ability as compared to RF-MEMS reconfigurable antennas. Reconfigurable antennas using varactor diodes have tuning ability based on integrating a variable capacitor into the antenna structure. The capacitance of the varactor can be varied by varying the biasing voltage [27].

Optical reconfiguration techniques rely on photoconductive switching elements [36]. The optical switches incorporated into an antenna structure become conductive once they are subjected to a laser beam. The integrated laser diodes generate the laser beam. Mechanically reconfigurable antennas can be achieved by altering the structure of the source antenna using actuators [34]-[35]. Finally, reconfigurable antennas can be implemented using smart materials such as meta-materials ferrites, and liquid crystals, dielectric fluids, etc.

The corresponding reconfigurability for each of the four-reconfiguration techniques can be obtained either by a change in the antenna surface current distribution, a change in the antenna physical structure, a change in the feeding network, or a change in the antenna radiating edges. The change in one parameter in the antenna characteristics may affect the other parameters. Therefore, RF antenna designers should be careful during the design stage to analyze all the characteristics simultaneously to achieve the required reconfiguration properties [27].

### **I.5.5 Motivations for Designing Reconfigurable Antennas**

The new era of antenna design must generate antennas that are cognitive and adjust to the environment and ever-changing surrounding conditions. Also, there is a need for antennas that can overcome failures and swiftly respond to new developments. Cognitive radio, multiple-input multiple-output (MIMO) channels, on-body networks, satellites, and space communication platforms are all possible applications for the integration of highly versatile, reliable, and efficient reconfigurable antennas. In this section, the design of reconfigurable antennas that are proposed to service different practical wireless communication applications is discussed [30].

### **I.5.6 Advantages and Disadvantages of Reconfigurable Antennas**

- **Advantages:**

Reconfigurable antennas can support more than one wireless standard, and deliver the same performance as that of multiple antennas. Hence, reconfigurable antennas have the following advantages [27].

- ⇒ Low cost, low volume, simple integration, and good isolation between different wireless standards.
- ⇒ Low front-end processing that means no need for front-end filtering and good out-of-band rejection.

- ⇒ Best candidate for software-defined radios which can adapt to new surroundings
- ⇒ Change functionality as per the mission changes, act as a single element or as an array, providing narrowband or wideband as per the requirements.

The cost of the reconfigurable antennas can be linked to different parameters as summarized below:

- ⇒ Design of the biasing network for activation/deactivation of the elements in the antenna structure,
- ⇒ Required power consumption of active components,
- ⇒ Generation of harmonics and intermodulation products
- ⇒ Fast tuning of the antenna radiation characteristics to assure the correct functioning of the system.

- **Disadvantage:**

Although reconfigurable antennas have many advantages, they also have disadvantages. Among these harms, we can cite [27]

- ⇒ More expensive than conventional antennas due to the use of active components.
- ⇒ High energy consumption (active components to be polarized continuously).
- ⇒ Design and simulation difficulties due to the integration of active components in the antenna (the need to use packages, polarization circuits).

## **I.6 Conclusion**

In this chapter, we have covered basic specifications of millimeter waves with their applications, microstrip antennas, and reconfigurable antennas and their necessity in the field of telecommunications and the classifications of reconfigurable antennas. Likewise, techniques and the different types of reconfigurability have been discussed, followed by the advantages and disadvantages of these reconfigurable antennas. To have the reconfiguration, we must add active components (PIN diode), which requires a detailed view of them in the next chapter.

# ***CHAPTER II***

# **DESIGN OF THE RECONFIGURABLE ANTENNA**

## II.1 Introduction

The evolution and technological development make a radical change in the field of electronics especially in wireless telecommunications, where this recent evolution offers a new perspective and sophisticated means such as reconfigurable antennas and their importance in improving everyday life.

Reconfigurable antennas can be mainly divided into four categories: frequency-reconfigurable antenna, polarization-reconfigurable antenna, pattern-reconfigurable antenna, and multiparameter-reconfigurable antenna. In recent years, the pattern-reconfigurable antenna is attracting more and more attention, as it is very useful for systems, which suffer from multipath interference. The pattern-reconfigurable antenna is capable of enhancing system security, improving communication reliability, and reducing energy loss to better enhance the performance of the whole system.

In this chapter, we will see the steps of antenna design from the conventional patch antenna to the reconfigurable antenna, and how it could radiate at different directions using the PIN diodes.

For the simulation tool, there are several dedicated electromagnetic simulators for the design of mm-wave components (printed antennas, HF filters, etc.). Among these simulators, we can cite for example the HFSS, ADS Momentum, IE3D, FEKO et CST MICROWAVE STUDIO. In our study, we will use HFSS.

## II.2 Antenna Geometry

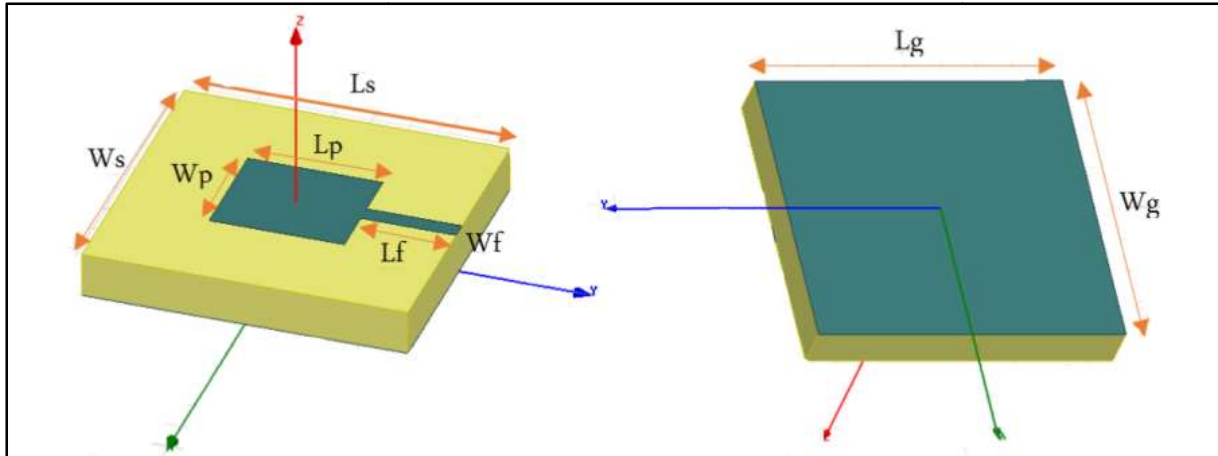
In this section, we propose a design of a conventional patch antenna. First, we will consider two antenna parameters to be optimized, in order to design a millimeter-wave antenna operating at 60 GHz. Then, the antenna shape will be modified to give a manual reconfiguration to the antenna. Thus, the considered parameters are:

- ∇ The reflection coefficient to determine the resonant frequency “60 GHz”.
- ∇ The radiation pattern to determine the geometry configuration that leads to controlling the antenna radiation pattern using RF switches.

Finally, our aim is to have an antenna that emits millimeter waves in different directions.

### II.2.1 Conventional Patch Antenna

First, we start with a rectangular patch antenna, using the equations cited in the first chapter (I.1) (I.2) (I.3) (I.4) (I.5) and (I.6).



**Figure II.1:** Geometry of the conventional patch antenna.

The basis of this antenna consists of a substrate surrounded by two conductor's materials, which are grounded from the bottom. The patch and the feed are on the top. The antenna is fed using a 50 Ohm microstrip line. The ground, patch and feed are considered as a perfect electrical surface "perfect E", and the substrate material is "FR4 epoxy" having a relative permittivity of  $\epsilon_r=4.4$  and dielectric loss tangent 0.002.

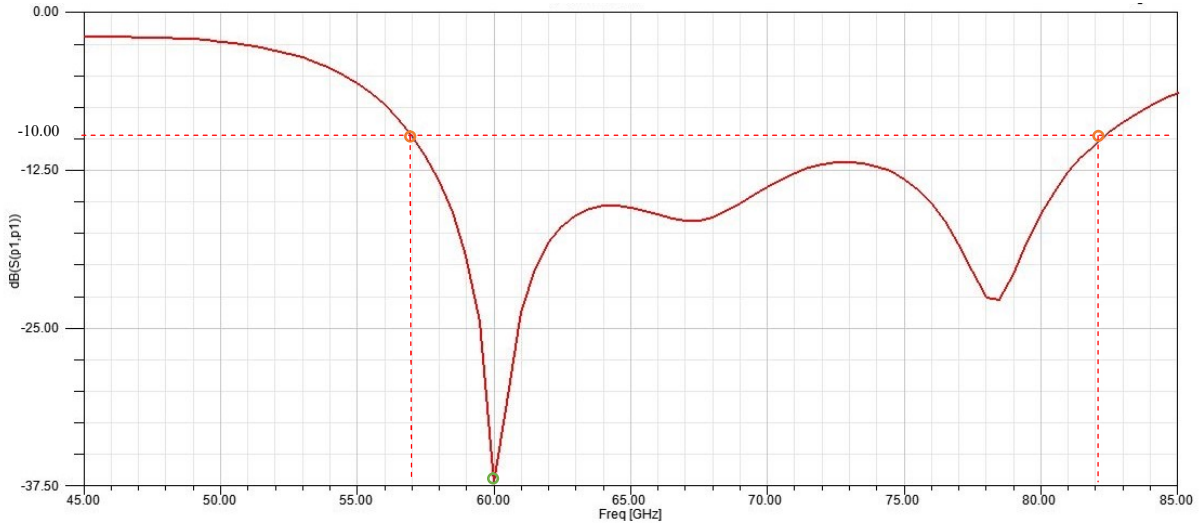
The substrate and the ground of the antenna have the same width  $W=4\text{mm}$  and the same length  $L=4.2\text{mm}$ . The substrate of this printed antenna has a Height of  $h=0.6\text{mm}$ , the total size of the substrate is  $4 \times 4.2 \times 0.6\text{mm}^3$ . As for the total size of the patch and the feed are  $1.519 \times 1.77\text{mm}^2$  and  $0.23 \times 1.25\text{mm}^2$  respectively. Table II.1 summarizes the different antenna parameters.

**Table II.1:** Antenna parameters.

parameters	$W_g$	$L_g$	$W_p$	$L_p$	$W_f$	$L_f$	$h$	$W_s$	$L_s$
dimensions	4mm	4.2mm	1.519mm	1.77mm	0.23mm	1.25mm	0.6mm	4mm	4.2mm

The obtained result of reflection coefficient " $S_{11}$ " for this conventional antenna is shown in Figure II.2. The resonant frequency of the antenna is the frequency at which the reactance of the antenna is equal to 0. The plot shows two resonance points, the main one is at  $f=60\text{GHz}$  with  $-37\text{dB}$  of  $S_{11}$ .

The reflection coefficient also gives the operating bandwidth of the antenna. Antenna bandwidth is usually the frequency band over which the magnitude of the reflection coefficient is below  $-10\text{dB}$ . The bandwidth is the difference between the upper and lower frequencies results from the intersection of the curve and the straight line  $-10\text{dB}$  witch is [57; 82] GHz. So the Bandwidth is  $B_w=25\text{GHz}$ .

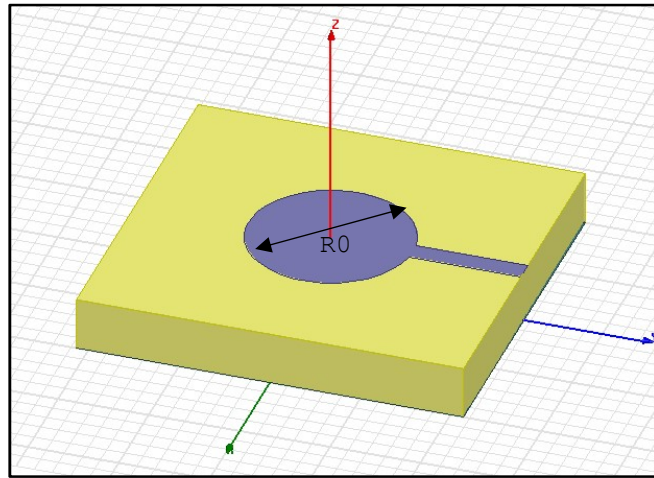


**Figure II.2:** reflection coefficient “ $S_{11}$ ” of step1.

In this simulation, we have a simple rectangular patch antenna with perfect radiation in resonant frequency 60 GHz but it’s not reconfigurable.

### II.2.2 Setup of RF switches

In this step, we suggest changing the shape of the radiator from rectangular to circle with radius  $R_0=0.9\text{mm}$  in order to create places for the RF switches.



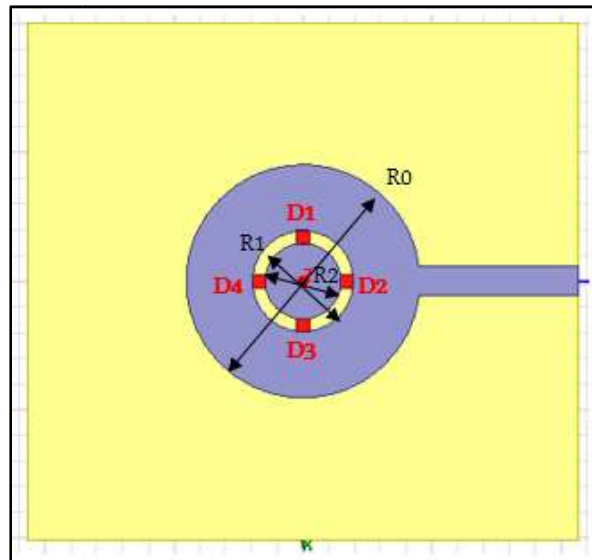
**Figure II.3:** Geometry of the Circle patch antenna.

Now, to set the diodes “MEMS switches” we are going to create a slot “disc” on the radiating patch by drawing two circles with tow different radius  $R_1=0.4\text{mm}$  and  $R_2=0.3\text{mm}$ . Table II.2 summarizes the different antenna parameters.

**Table II.2:** dimensions of the circle patch antenna.

parameters	$W_g$	$L_g$	$W_s$	$L_s$	$W_f$	$L_f$	$h$
dimensions	4mm	4.2mm	4mm	4.2mm	0.23mm	1.25mm	0.6mm
parameters	$R_0$	$R_1$	$R_2$				
dimensions	0.9mm	0.4mm	0.3mm				

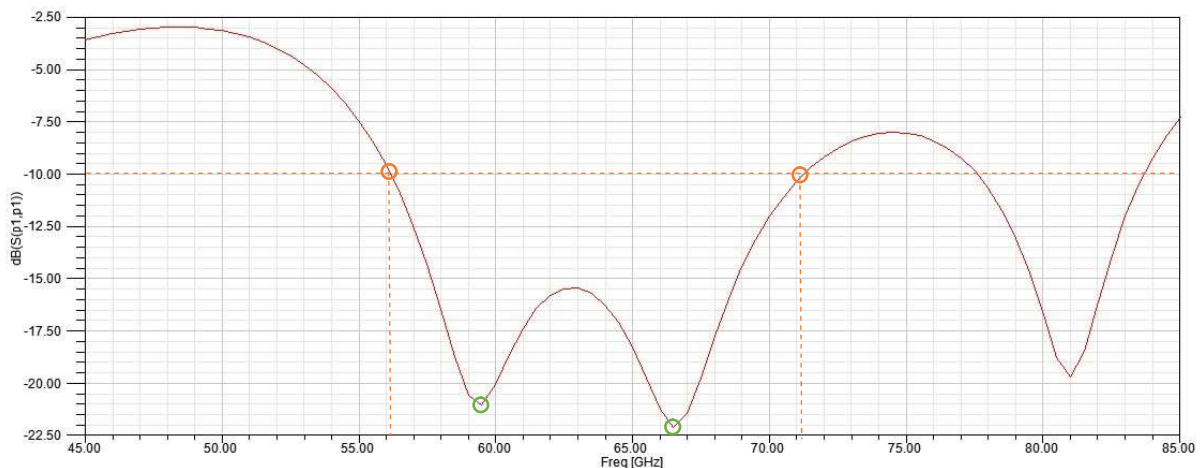
At the beginning, we suggest setting four MEMS switches as shown in the Figure II.4, the goal of setting it in the radiator is to control the electrical current flowing from the feed.



**Figure II.4:** Geometry of the Circle patch antenna after adding PIN diodes "D1, D2, D3, and D4".

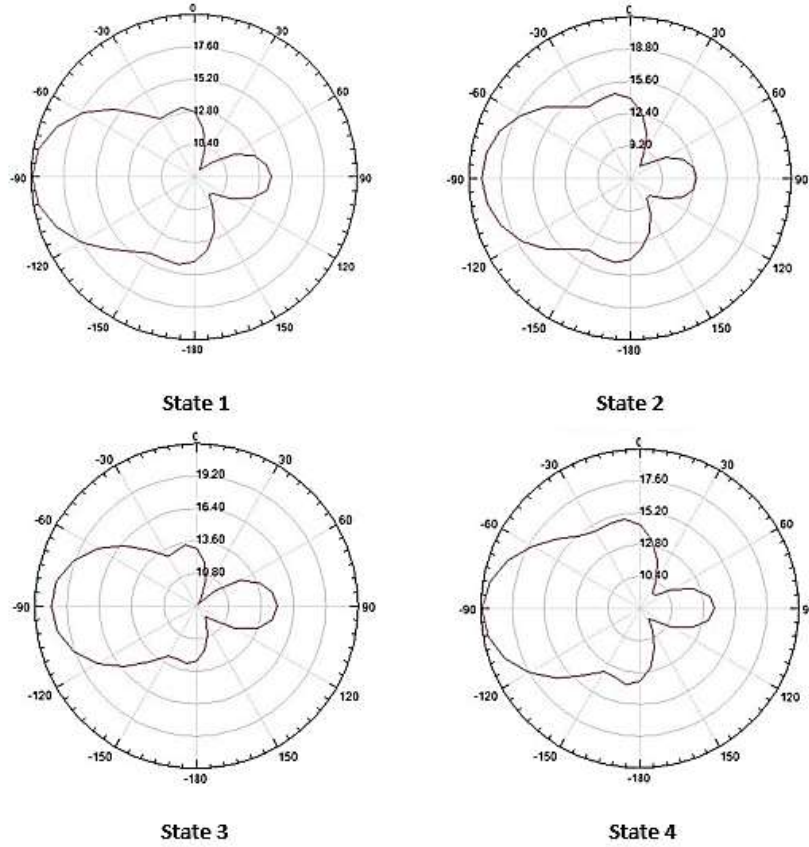
### II.2.2.1 Results

The reflection coefficient " $S_{11}$ " is illustrated in Figure II.5. In this design, the bandwidth became smaller starting from 56 GHz to about 71 GHz so that the obtained bandwidth is  $Bw=15$  GHz. For the resonant frequency of the antenna in this plot, we have two resonance points in  $f_1=59.5$  GHz ,  $-20.8$  dB and  $f_2=66.5$  GHz ,  $-24.2$  dB.



**Figure II.5:** obtained reflection coefficient " $S_{11}$ " with diodes "D1, D2, D3 and D4".

The obtained radiation patterns (azimuth plane) are shown in Figure II.6. These simulated configurations of different operation modes are summarized and presented in Table II.3. As indicated in the figures, we have a radiation antenna but it radiates to  $90^\circ$  in all states "in one direction".



**Figure II.6:** Simulated radiation patterns (azimuth plane) for different operation states.

**Table II.3:** operation states.

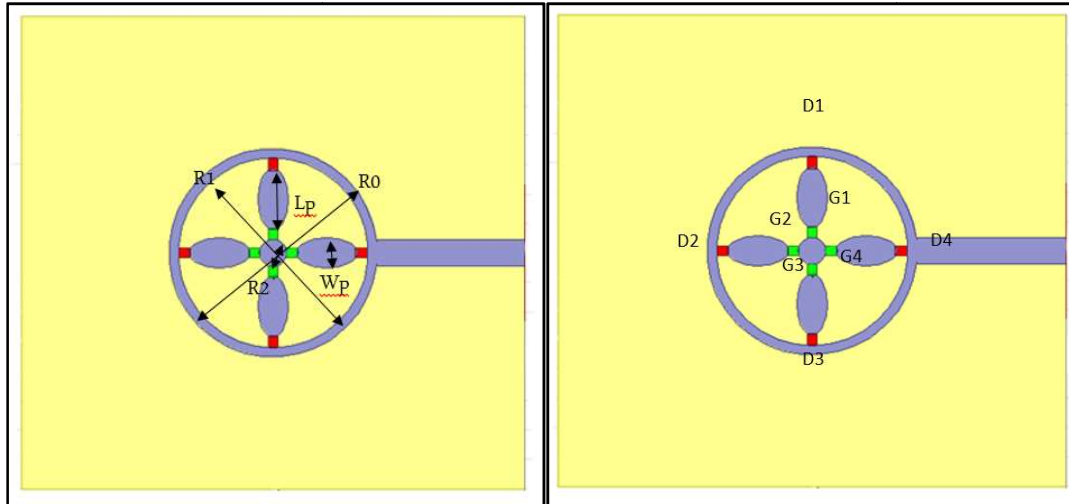
Operation state	MEMS switches			
	D1	D2	D3	D4
State 1	1	0	0	0
State 2	0	1	0	0
State 3	0	0	1	0
State 4	0	0	0	1

### II.2.3 Geometry Optimization

In this step, we want to control the current flow in the patch, by expand the slot “disc” and draw four ellipses connected to the central circle by four diodes as shown in the figure. For the slot, the first radius becomes  $R_1=0.8\text{mm}$ , and the second radius  $R_2=0.1\text{mm}$ . The ellipses have a length  $L_p=0.3\text{mm}$  and width  $W_p=0.4$ (without unit), The Table II.4 summarizes the different antenna parameters.

**Table II.4:** dimensions of the antenna with 8 diodes.

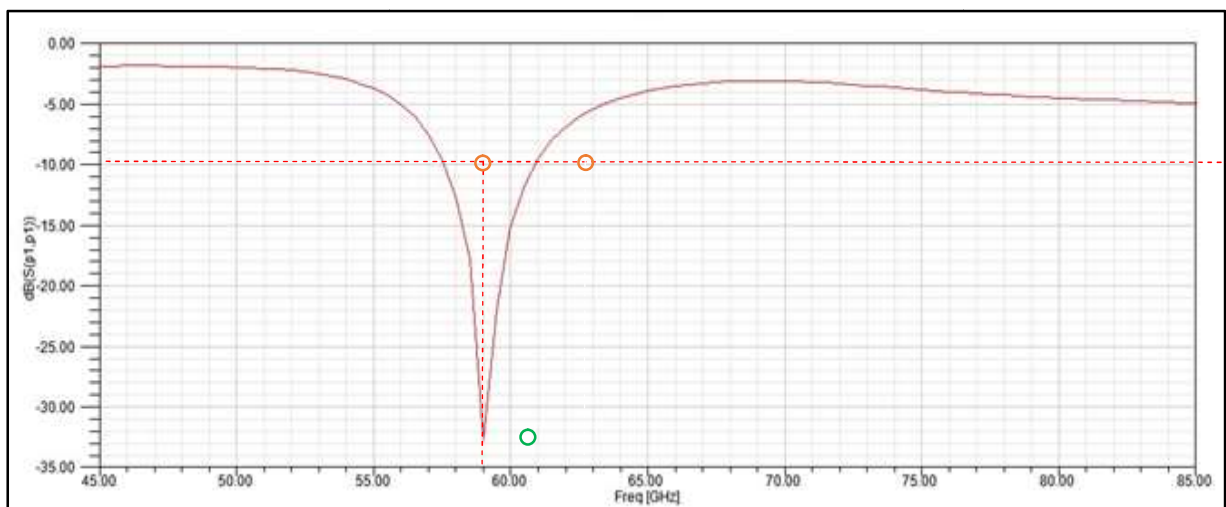
parameters	W <sub>g</sub>	L <sub>g</sub>	W <sub>s</sub>	L <sub>s</sub>	W <sub>f</sub>	L <sub>f</sub>	h
dimensions	4mm	4.2mm	4mm	4.2mm	0.23mm	1.25mm	0.6mm
parameters	R0	R1	R2	L <sub>p</sub>	W <sub>p</sub>		
dimensions	0.9mm	0.8mm	0.1mm	0.3mm	0.4		



**Figure II.7:** Geometry and parameters of the Circle patch antenna with the 8 diodes.

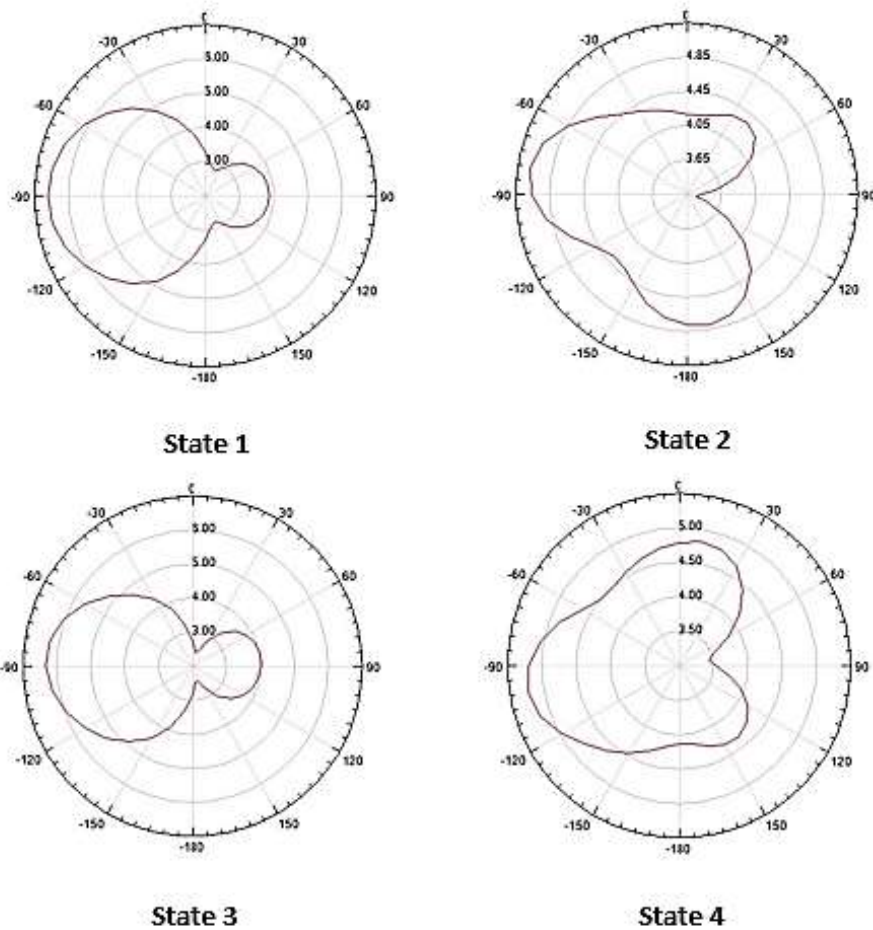
### II.2.3.1 Results

The reflection coefficient " $S_{11}$ " is illustrated in Figure II.8. In this state, the bandwidth became more small starting from 57.5 GHz to 60.9 GHz so that the bandwidth is  $Bw=3.4$  GHz. For the resonant frequency of the antenna in this plot, we have one resonance point at  $f_1=59$  GHz and  $-33$  dB of  $S_{11}$ .



**Figure II.8:** reflection coefficient " $S_{11}$ " of the antenna with the 8 diodes.

The radiation pattern in the azimuth plane is illustrated in Figure II.9



**Figure II.9:** Simulated radiation patterns (azimuth plane) for different operation states.

The simulated configurations of different operation states are summarized in Table II.5.

**Table II.5:** the different operation states.

Operation state	MEMS switches			
	D1G1	D2G1	D3G3	D4G4
State 1	11	00	00	00
State 2	00	11	00	00
State 3	00	00	11	00
State 4	00	00	00	11

The expansion of the slot contributed to an improvement in the reflection coefficient but the radiation still has one direction.

## II.2.4 Changing the Feeding Techniques

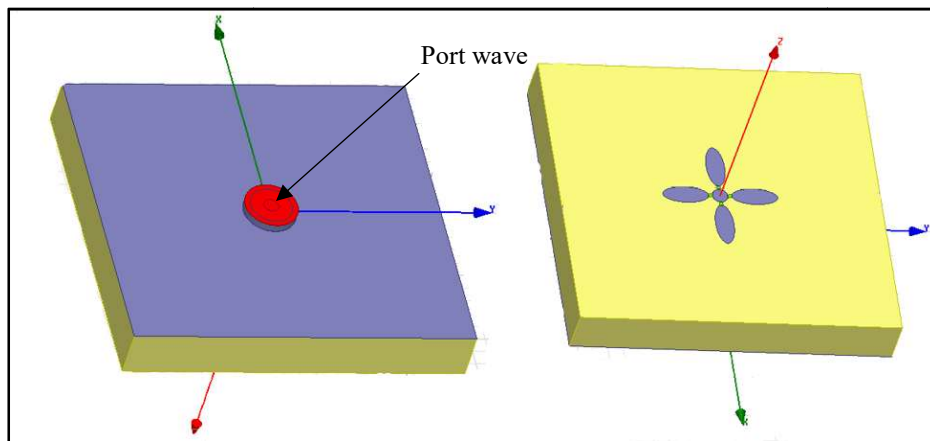
After the previous simulation, we could not find an antenna that emits millimeter waves in different directions. In order to achieve our goal, we suggest the change of the feeding technique from line feed to coaxial feed.

The coaxial feed consists of a cylinder of material “Pec” with radius  $R_a=0.09\text{mm}$ , it links between the port wave and the radiator “patch”, this cylinder surrounded by two cylinders like a disc also of material “Pec” with radius  $R_b=0.2\text{mm}$ ,  $R_c=0.3\text{mm}$ . The Table II.6 summarize the different coaxial feed parameters.

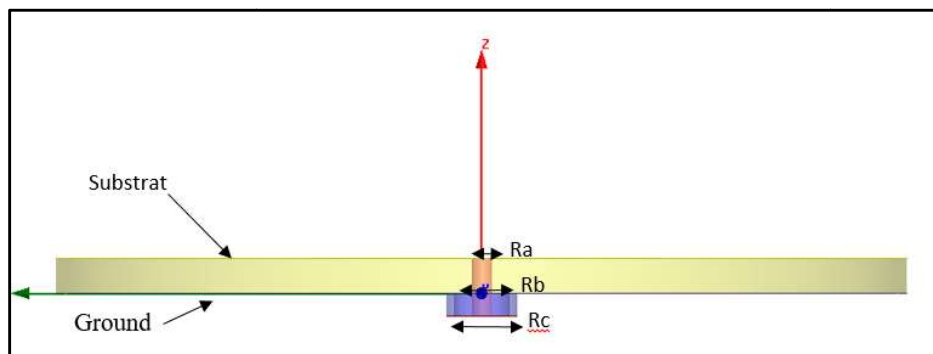
**Table II.6:** the dimensions of the antenna with 8 diodes.

parameters	$R_a$	$R_b$	$R_c$
dimensions	0.09mm	0.2mm	0.3mm

To create this feeding techniques we need to draw a circle in the ground of the antenna with a radius  $R_b$  and subtract it from the ground.



**Figure II.10:** Geometry of an antenna with a coaxial feed.



**Figure II.11:** Coaxial feed side view.

In this state, the antenna did not radiate we need to apply an optimization for all the parameters of our antenna. The goal of this optimization is to obtain a reflection coefficient with resonant frequency  $f=60\text{GHz}$ .

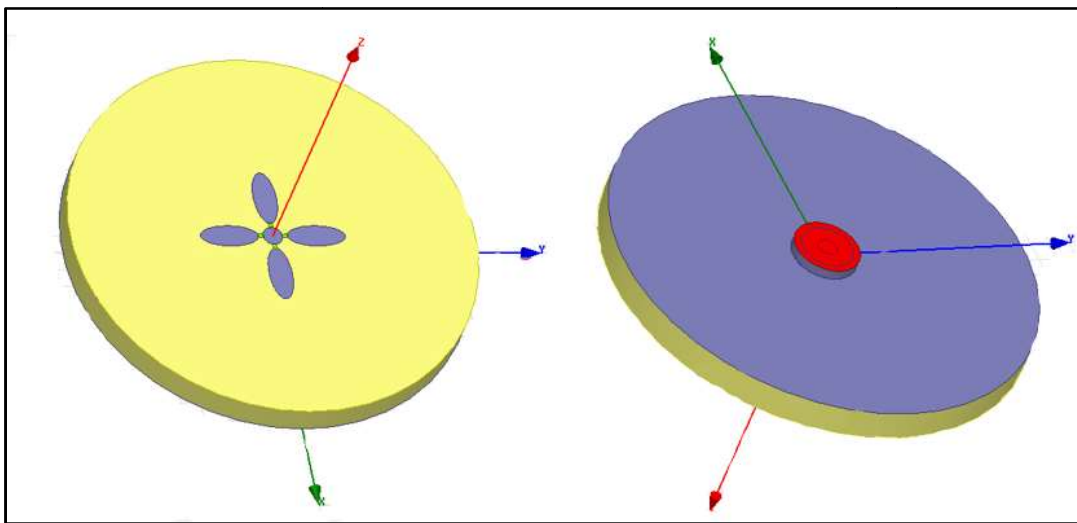
## II.2.5 Parametric Optimization

Before starting the optimization of all the parameters, we suggest to change the shape of the substrate from box to a cylinder in order to reduce the number of variables, instead of length and width, we only have a radius  $R_0=2.1\text{mm}$ , for fast optimization. Table II.7 summarizes the different coaxial feed parameters.

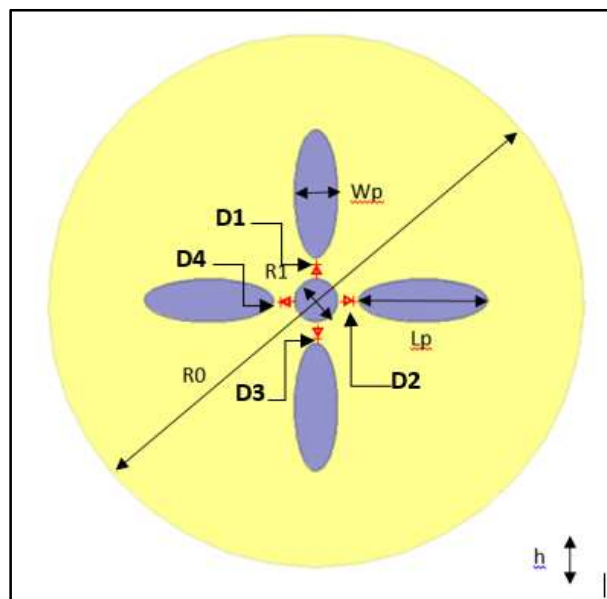
**Table II.7:** The dimensions of the antenna.

parameters	h	R0	R1	Wp	Lp	Ra	Rb	Rc
dimensions	0.6mm	2.1mm	0.1mm	0.4	0.3mm	0.09mm	0.2mm	0.3mm

We leave one of the diodes and deactivate the others.

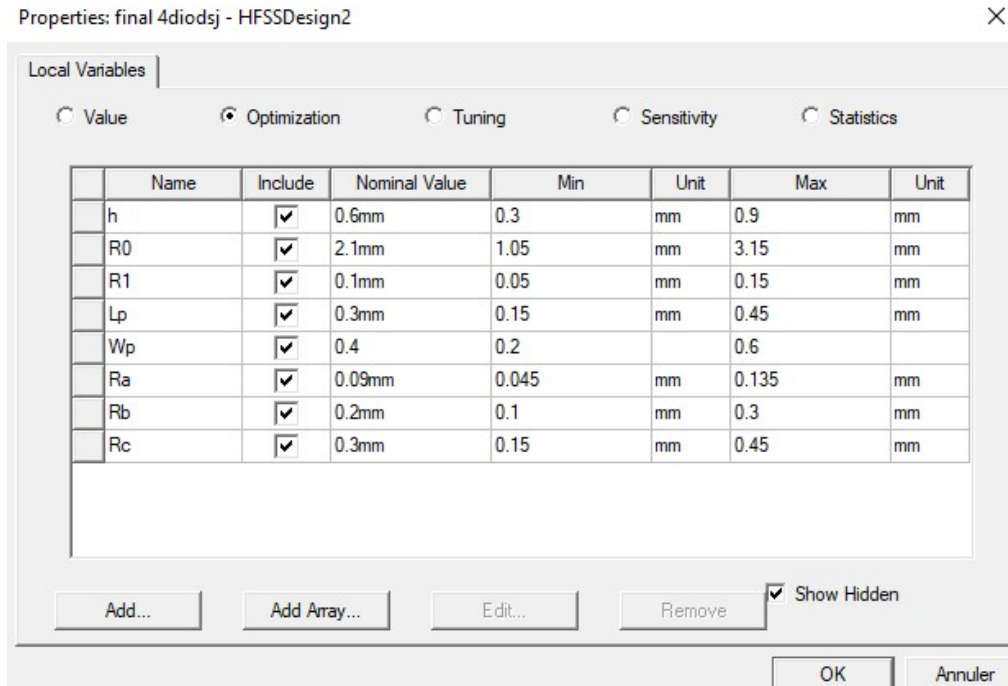


**Figure II.12 :** Geometry of an antenna with a cylindrical substrate.



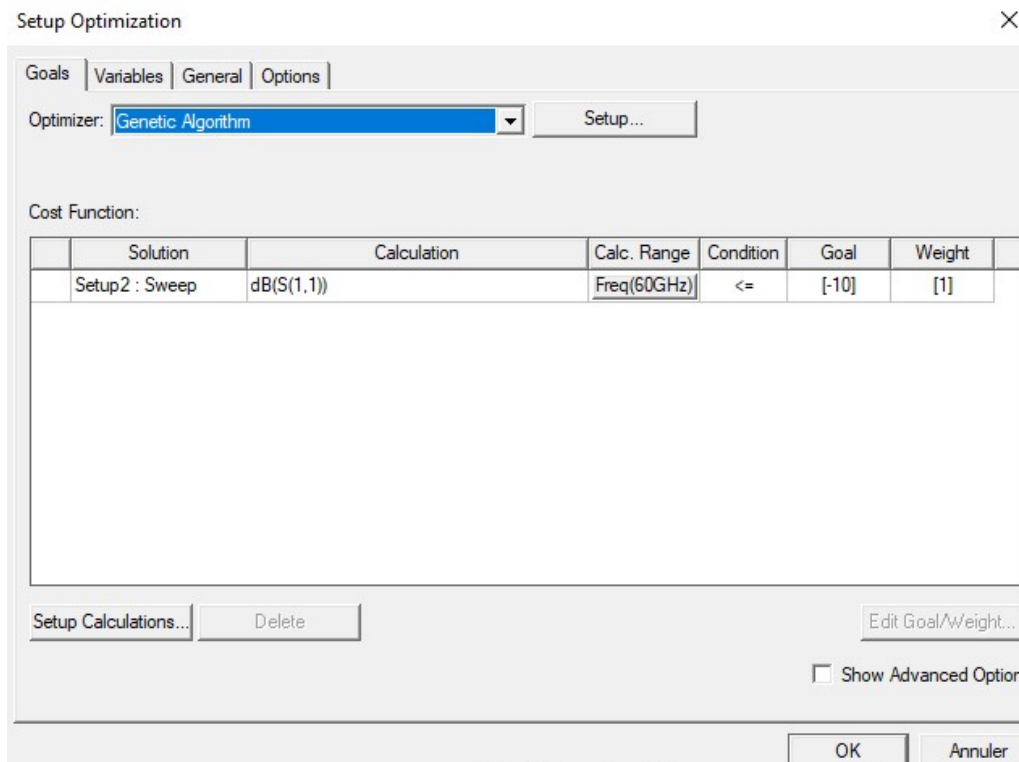
**Figure II.13 :** The dimensions of the antenna.

First, we open the window of the variable, and then we will check the parameters to optimize as shown in Figure II.14



**Figure II.14** : list of variables in HFSS.

After that, we open the window of setup optimization and we will define the goal. In our case, the  $S_{11}$  reflection coefficient should be less than -10dB in the resonant frequency  $f=60$  GHz.

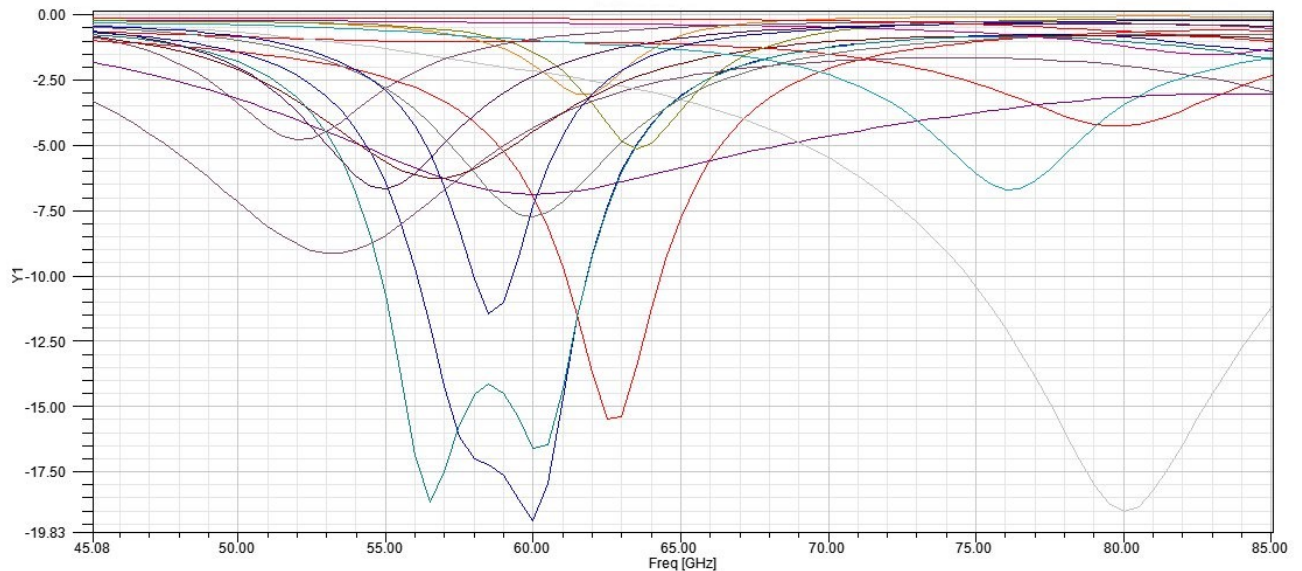


**Figure II.15** : Setup optimization.

After applying the parametric study, we have obtained many curves as shown in Figure II.16. We choose the closest curve to the frequency 60GHz. The parameters of the antenna became as shown in Table II.8

**Table II.8:** *The dimensions of the antenna.*

parameters	h	R0	R1	Lp
dimensions	0.2900mm	3.9000mm	0.2604mm	0.6510mm
parameters	Ra	Rb	Rc	Wp
dimensions	0.0900mm	0.2530mm	0.3220mm	0.3000



**Figure II.16 :** *Results of optimization of the reflection coefficient.*

### II.2.5.1 Diodes Configurations

After the optimization and getting an antenna with a perfect reflection coefficient, now we choose the appropriate diode possibilities. We have a finite number of possibilities, and this is due to the number of diodes, where we have four diode, so we have  $4^2=16$  possibilities. After evaluating the obtained results of all possibilities, we choose the configuration of each diode is activated alone as shown in Table II.9, which permits to obtain four basic operation states for this antenna.

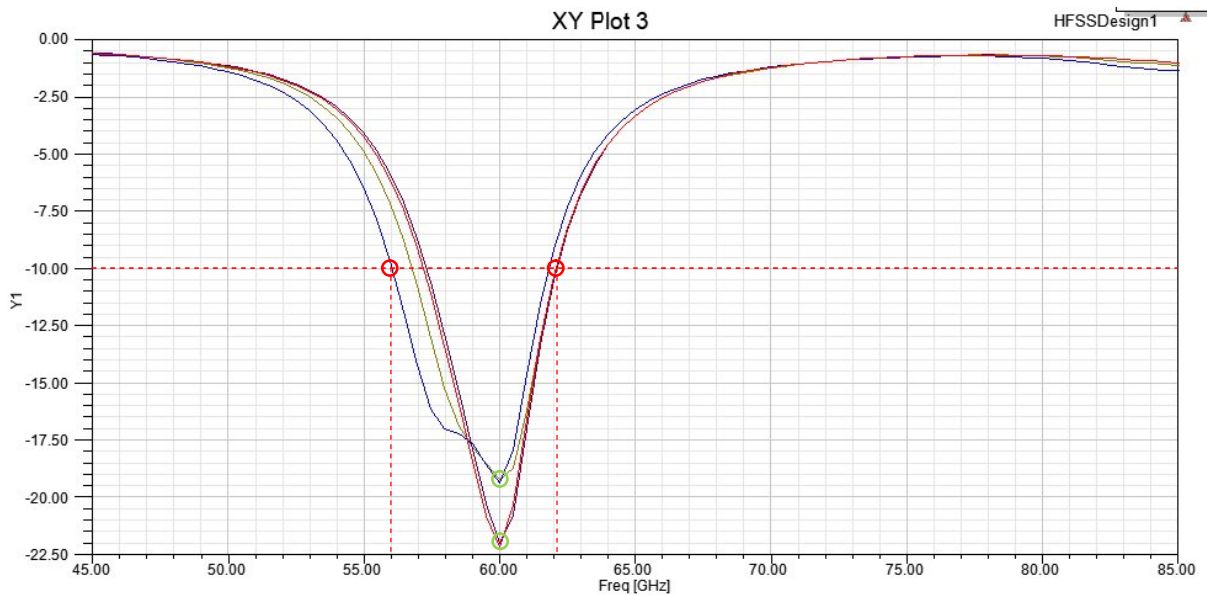
**Table II.9** : The different operation states.

Operation state	MEMS switches			
	D1	D2	D3	D4
State 1	1	0	0	0
State 2	0	1	0	0
State 3	0	0	1	0
State 4	0	0	0	1

These possibilities gave us a pattern-reconfigurable antenna that emits at millimeter waves in four different directions. Every PIN diode configuration gives a radiation pattern in a different angle from  $0^\circ$  to  $360^\circ$  with a step angle of  $90^\circ$  as shown in Figure II.18.

### II.2.5.2 Results

The reflection coefficient  $S_{11}$  is illustrated in Figure II.17. According to these plots, the bandwidth of all the configurations starts from 56 GHz to 62.2 GHz so that the obtained bandwidth is  $Bw=6.2$  GHz. For the resonant frequency of the antenna, in these plots all the curves the resonant frequency is  $f=60$ GHz in  $-22$ dB.

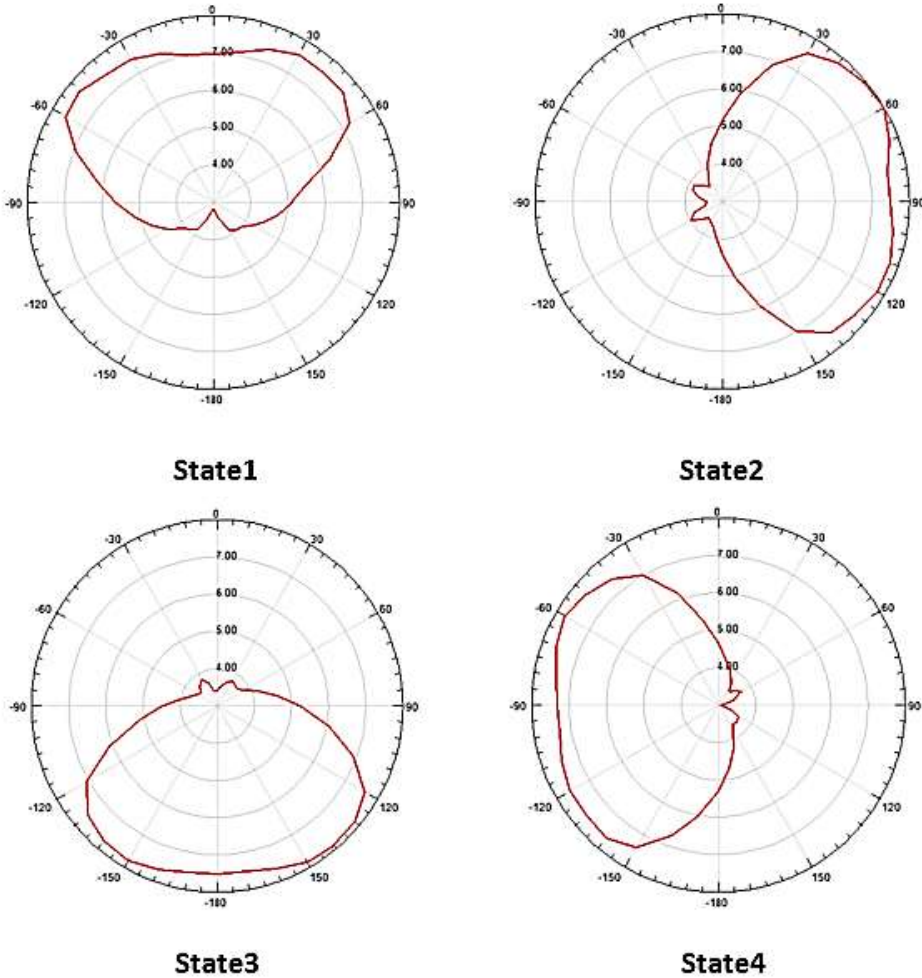


**Figure II.17**: The curves of the reflection coefficient " $S_{11}$ " of state 1, 2, 3 and 4.

The radiation pattern in the azimuth plane is shown in Figure II.18. Four basic operations modes are obtained for the proposed antenna. Sequentially switching operation states from state 1 to state 4 can rotate the main radiation beam by  $90^\circ$  per step starting from  $0^\circ$  to  $360^\circ$  in the azimuth plane.

In the state1, when the  $D_1$  is ON and  $D_2$ ,  $D_3$  and  $D_4$  are OFF, the electrical current flows just in the ellipse connected to the diode  $D_1$ , the antenna emits the millimeter waves to the corners  $-30^\circ$ ,  $0^\circ$ , and  $30^\circ$ . The same remark is observed in other states. In State 2, the antenna radiate to the corners  $60^\circ$ ,  $90^\circ$ , and  $120^\circ$ . In State3, the antenna radiate to the corners  $150^\circ$ ,

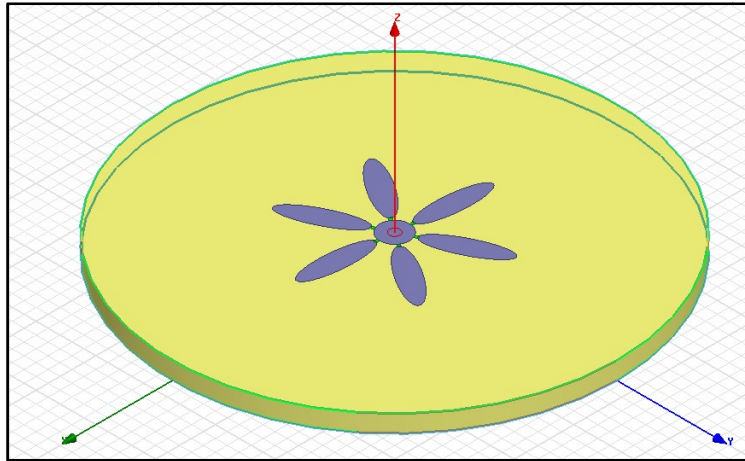
-180°, and -150°. In State 4, the antenna radiate to the corners -120°, -90°, and -30°. The curve of the radiation pattern moves at a corner of 90°. We notice that the waves follow the same direction as the current.



**Figure II.18:** Simulated radiation patterns (azimuth plane) for different operation states.

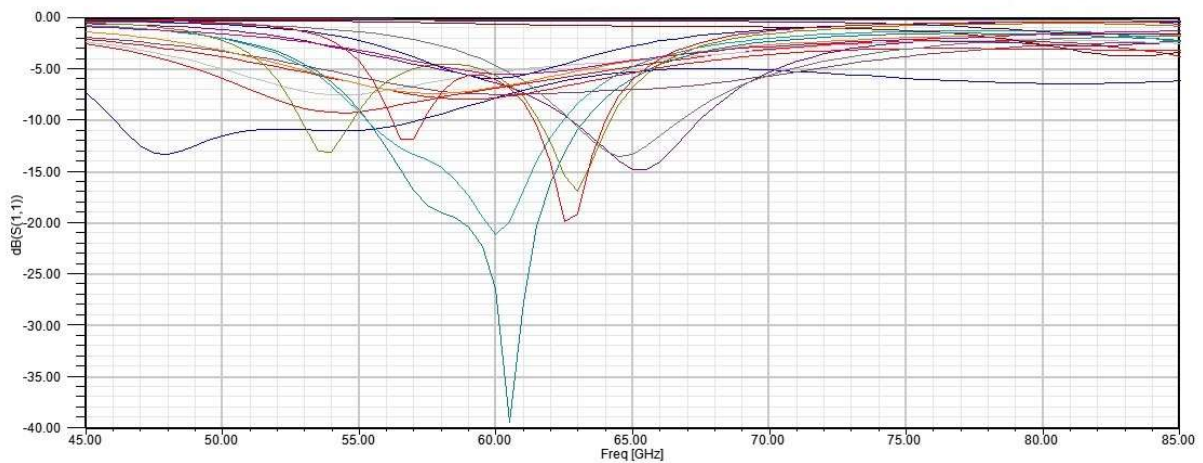
**II.2.6 Antenna Enhancement**

Our aim in this simulation is to design an antenna that emits in millimeter waves spectrum in different directions. Every direction is at a corner separately, that is why we wanted to improve the antenna, and this is by adding two ellipses connected with the central circle by two diodes. The designed antenna is shown in Figure II.19.



**Figure II.19** : Geometry of the antenna with six diodes.

The obtained simulation results for this configuration did not get the desired results, thus we need to do another optimization by applying the last method of optimization as shown in the previous Figure II.14 and II.15, with the same goal.



**Figure II.20** : Results of optimization for the reflection coefficient.

After the optimization operation, we choose the curve closest to the frequency 60GHz, and the parameters of the antenna became as shown in Table II.10.

**TabII.10**: The dimensions of the antenna.

parameters	h	R0	R1	Lp
dimensions	0.2900mm	3.7200mm	0.2480mm	0.9300mm
parameters	Ra	Rb	Rc	Wp
dimensions	0.08649mm	0.2418mm	0.3069mm	0.279

### II.2.6.1 Enhanced Antenna Diodes Configurations

After optimization and calculation of the dimensions of the antenna, there is a large number of possibilities, this number depends on the number diodes, so we have  $6^2$  possibilities. We will not be able to experiment with this large number of possibilities, so we will rely on previous observations, which is the emission of mm-waves in the same direction as the flow of the current in the radiator. We have chosen these possibilities shown in Table II.11 and we got the required results, twelve basic operation states are obtained for this antenna.

**Table II.11:** The different operation states.

Operation state	PIN diodes state					
	D1	D2	D3	D4	D5	D6
State 1	1	0	0	0	0	0
State 2	1	1	0	0	0	0
State 3	0	1	0	0	0	0
State 4	0	1	1	0	0	0
State 5	0	0	1	0	0	0
State 6	0	0	1	1	0	0
State 7	0	0	0	1	0	0
State 8	0	0	0	1	1	0
State 9	0	0	0	0	1	0
State 10	0	0	0	0	1	1
State 11	0	0	0	0	0	1
State 12	1	0	0	0	0	1

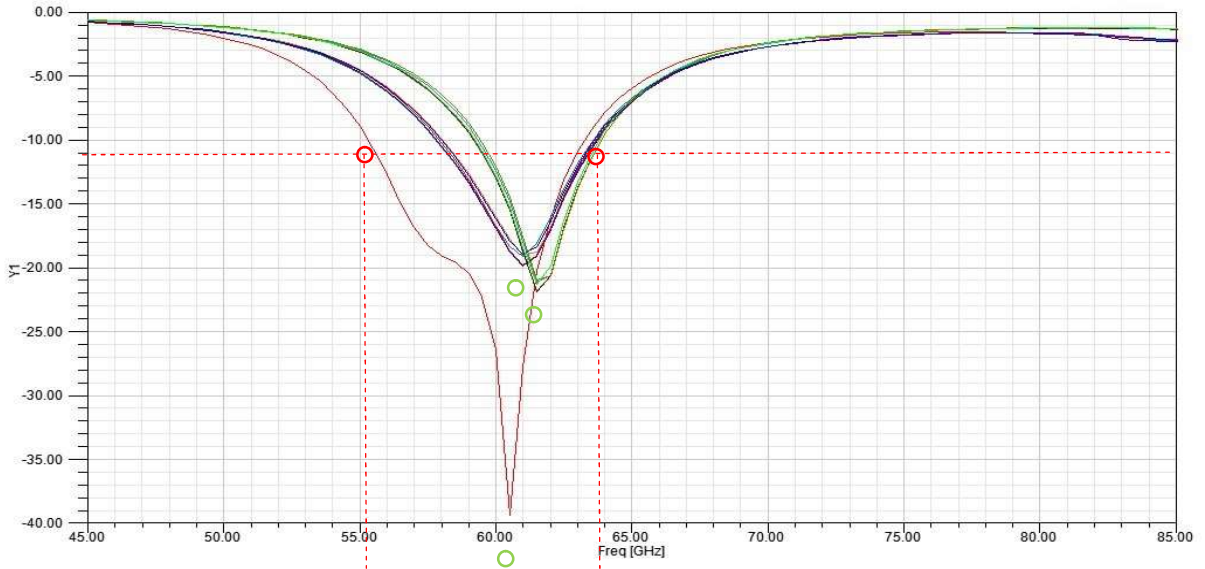
### II.2.6.2 Results

The  $S_{11}$  reflection coefficient is illustrated in Figure II.21. According to these plots, the bandwidth became more small starting from 55.5 GHz to 64 GHz, and the bandwidth is  $Bw=8.5$  GHz. For the resonant frequency of this antenna, each state has a specific resonant frequency as shown in Table II.12.

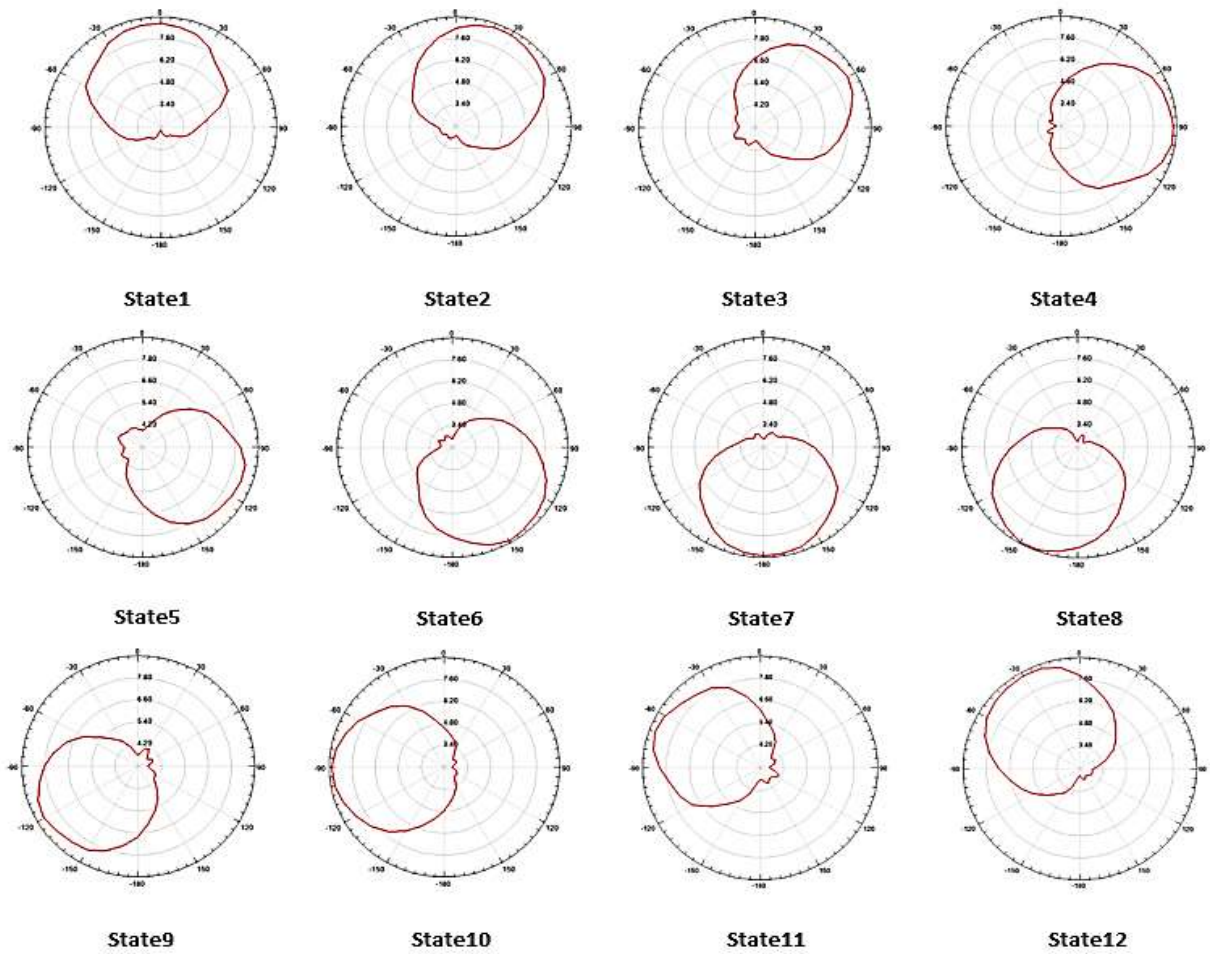
**Table II.12:** The different resonant frequencies.

states	1	2	3	4	5	6	7	8	9	10	11	12
X(GHz)	60.5	61	61.5	61	61.5	61	61.5	61	61.5	61	61.5	61
Y(dB)	-18.7	-18.9	-21.2	-19.8	-20.9	-19	-31.8	-19	-21.8	-19	-21.8	-19.8

The radiation patterns in the azimuth plane are shown in Figure II.22. Twelve basic operation states (state 1 to state 12) are obtained for this proposed antenna. Sequentially switching operation states from state 1 to state 12 can rotate the main radiation beam by  $30^\circ$  from  $0^\circ$  to  $360^\circ$  in the azimuth plane.



**Figure II.21:** The curve of the reflection coefficient "S11" for different operation states.



**Figure II.22:** Simulated and measured radiation patterns (azimuth plane) for different operation states.

### **II.3 Conclusion**

In this chapter, we designed a reconfigurable antenna for mm-wave, we started with a rectangular patch antenna, after the changes, simulation, and optimization we found two reconfigurable antennas with radiation pattern selectivity using PIN diode switches. By controlling the states of these RF switches, the first antenna of four diodes can operate at 4 different states. The direction of radiation can rotate by  $90^\circ$  per step from  $0^\circ$  to  $360^\circ$  in the azimuth plane. The second antenna of six diodes can operate at 12 different modes. The direction radiation can rotate by  $30^\circ$  per step from  $0^\circ$  to  $360^\circ$  in the azimuth plane.

# **CHAPTER III**

## **RESULTS AND DISCUSSIONS**

### **III.1 Introduction**

In the previous chapter, we have applied a parametric study that allows us to determine the best geometry for reconfiguration, and the optimal values of the different dimensions of the antenna in order to keep the same resonating frequency. To show the effect of reconfigurability on the radiation pattern of the antenna, we placed 6 PIN diodes in the antenna surface in order to change the direction of the radiation pattern by varying the configuration of these switching diodes.

In this chapter, we will discuss the obtained simulation results of our proposed reconfigurable antennas. These obtained results are calculated by applying a solution frequency of 60 GHz to be solved in High-Frequency Structure Simulator (HFSS). HFSS is a commercial finite element method solver for electromagnetic structures. HFSS is one of the most popular commercial tools used in antenna design, and the design of complex radio frequency electronic circuit elements including filters, transmission lines, and packaging.

### **III.2 Antenna Operating Principle**

The reconfigurable radiation pattern antenna was simulated using HFSS, realized and characterized at the operating frequency 60 GHz. To do the simulation, we suggested six diodes that allow us to obtain twelve states of configuration. The antenna resonant frequency is at 60 GHz, which can cover the 5G future bands, by turning PIN diodes placed on the patch antenna (ON-OFF), it covers many directions. Figure III-1 shows the simulated reflection coefficient for different configurations of the designed antenna. As it is clear from the  $S_{11}$  results, the resonant mode is centered at about 60-62GHz.

The PIN diodes are placed on the patch. Note that we have applied the 10 dB threshold of the return-loss to define the operating bandwidth.

### **III.3 Results and Discussion**

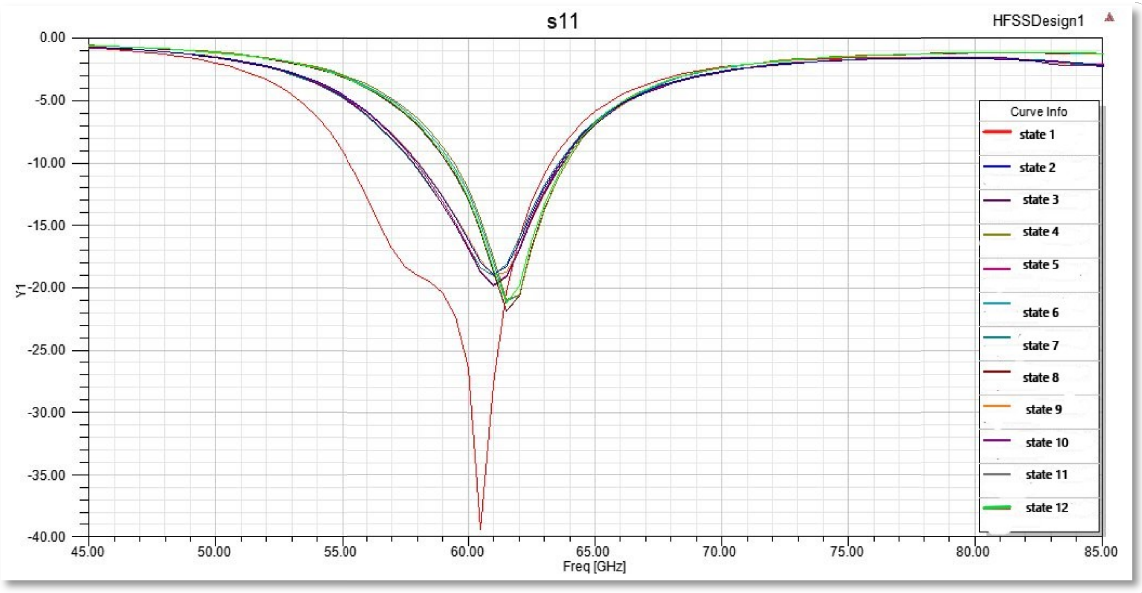
The designed antenna was investigated by calculating its impedance matching around the 60GHz spectrum and its radiation properties (gain, efficiency, and radiation patterns). The implantation of switches as described above allows to electronically controlling the radiated beam at the operating frequency by activating or deactivating one elementary dipole and/or directors(diodes pin). In order to better understand the radiation mechanism of the structure, we have analyzed simulated surface current distributions inside the antenna and the 2D radiation patterns for all the considered modes.

We present simulated results as  $S_{11}$ , return loss, VSWR, impedance matching, gain, efficiency, and radiation patterns behavior.

#### **III.3.1 Reflection Coefficient**

The reflection coefficient ( $S_{11}$ ) characteristic of the antenna for the different configurations of the diodes is shown in Figure III- 1. Accordingly, this antenna is covering approximately the same bandwidth; except in one state. The resonance frequency of different

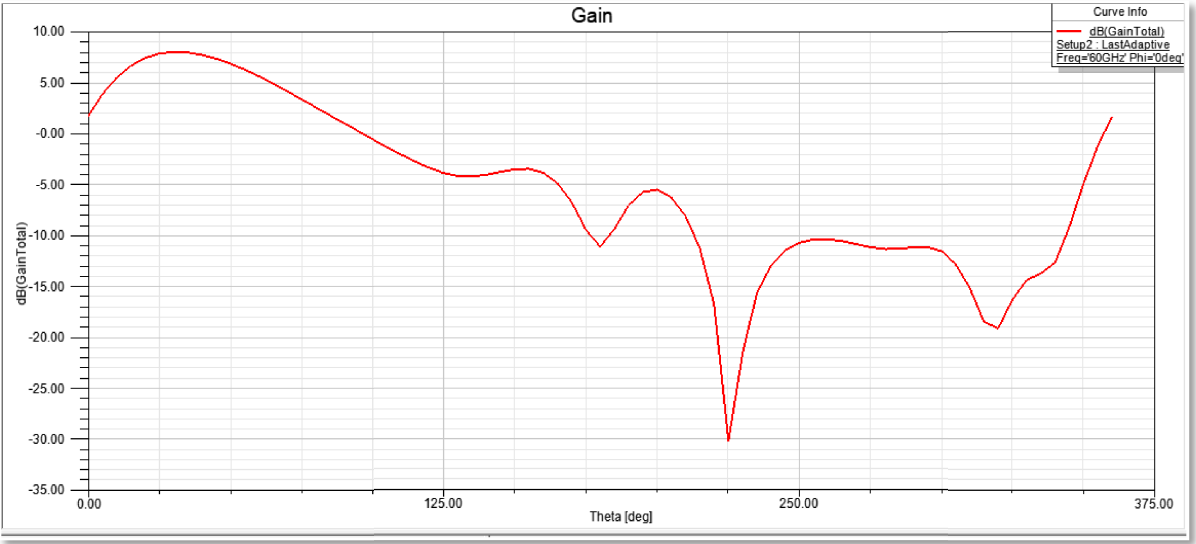
configuration is kept in the interval between 60 GHz and 61,5 GHz. A good adaptation is obtained as the  $S_{11}$  curve is between -20 dB and down to -39 dB.



**Figure III.1:** Reflection coefficient ( $S_{11}$ ) of the antenna in all states.

### III.3.2 Gain Characteristic

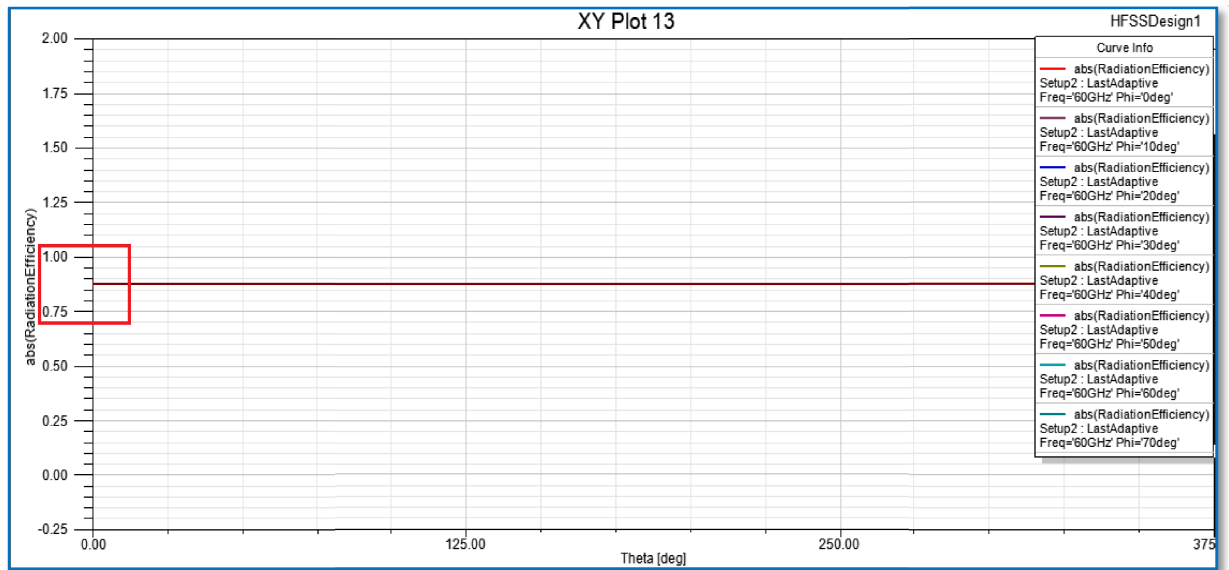
Figure III.2 illustrates the gain plot versus directions; it is observed that the proposed antenna has a good performance in terms of gain. The antenna has a peak gain of 8dBi at the resonant frequency, which illustrates relatively high radiation efficiency.



**Figure III.2.** Plot of gain versus theta.

### III.3.3 Efficiency

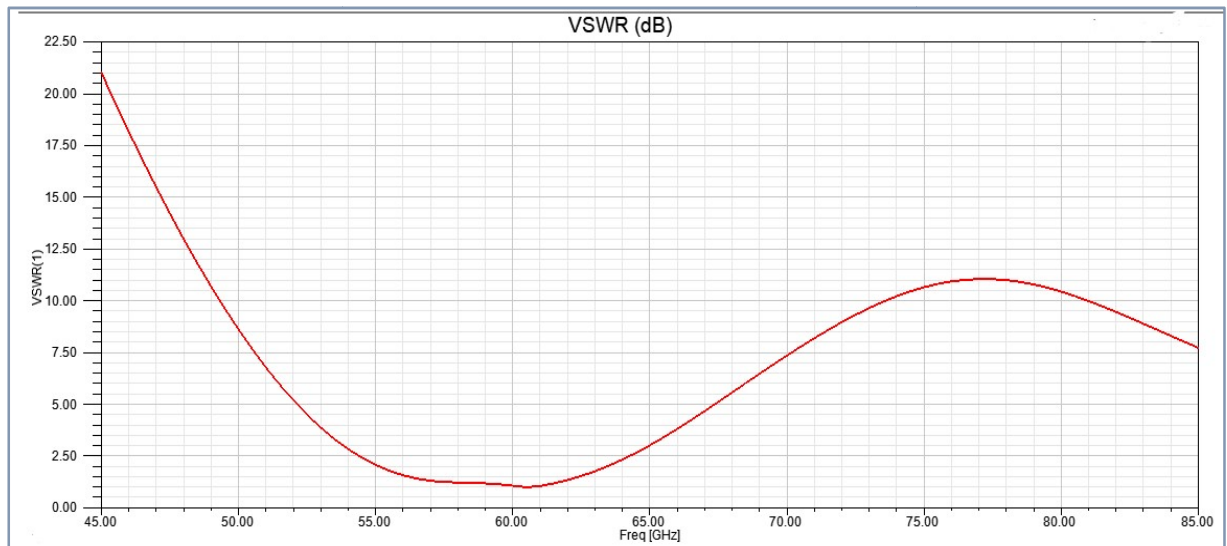
As shown in FigureIII.3, the obtained efficiency is from 85-95 % within the operating frequency band.



**Figure III.3** Radiation efficiency.

### III.3.4 VSWR characteristics

The VSWR as a function of frequency is shown in Figure III.5; it describes the power reflected from the antenna. The parameter VSWR is a measure that numerically describes how well the antenna is impedance matched to the radio or transmission line it is connected to. In this case, we see that the VSWR is lower than 2 at the resonance frequency which means that the antenna matching is well realized.

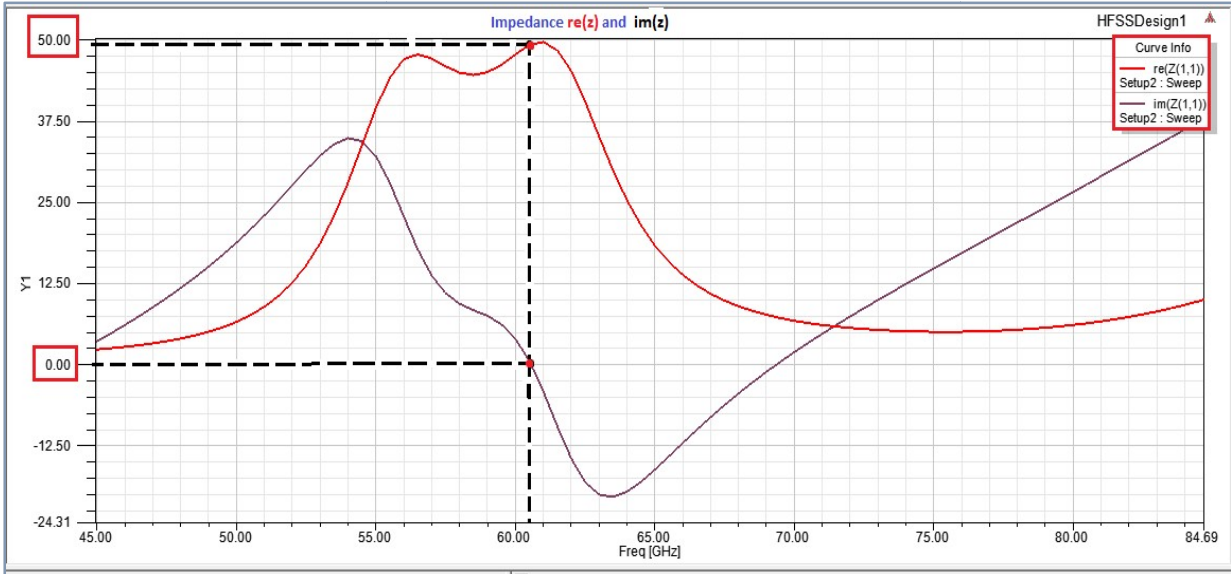


**Figure III.4** Plot of antennas VSWR versus Frequency.

### III.3.5 Input Impedance

By observing Figure III.5, we note here that the antenna resistance (real part of the antenna impedance) at the resonance frequency is equal to 50 Ohms, and for the reactance of

the antenna (imaginary part of antenna impedance) is equal to 0, which means that the antenna has a good impedance matching at the resonant frequency.



**Figure III.5.** Plot of antenna's impedance versus Frequency

### III.3.6 Table of Operation Modes

The obtained simulation information of different operation states are summarized in Table III.1. The antenna has quite good gain and it ranges from 6.8 to 8.10 dB as shown in Table III.1. The maximum obtained gain is 8.1 dB when the antenna transmits at the 360° angle (state 12), the lowest gain is 6,83 on the 5th state at 120°. The first, sixth and the twelfth states have the highest bandwidth which reaches 8 GHz. For other states, it has almost the same range of values of gain and bandwidth.

### III.3.7 Radiation Characteristics

Tab III.2 presents the modes of operation using switching pin diodes and their obtained angles in which the antenna radiated. As shown in Figure III.6, the proposed antenna has 12 basic operation states (one or two-adjacent ON-state pin diodes switch). Accordingly radiating at 12 different directions in the azimuth plane, by changing the pin diodes configuration, the antenna can be steered with a step angle of 30° to cover all possible directions. i.e., from state 1 to state 12, the radiation angles vary from 0° to 330° with step increment of 30°. Thus, this result indicates that this designed antenna can cover the whole azimuth plane. It also manifests that each operation state provides corresponding main-beam direction and demonstrates the radiation pattern having a reconfigurable characteristic.

**Table III.1:** Operation modes of the antenna (0: OFF \_ 1: ON)

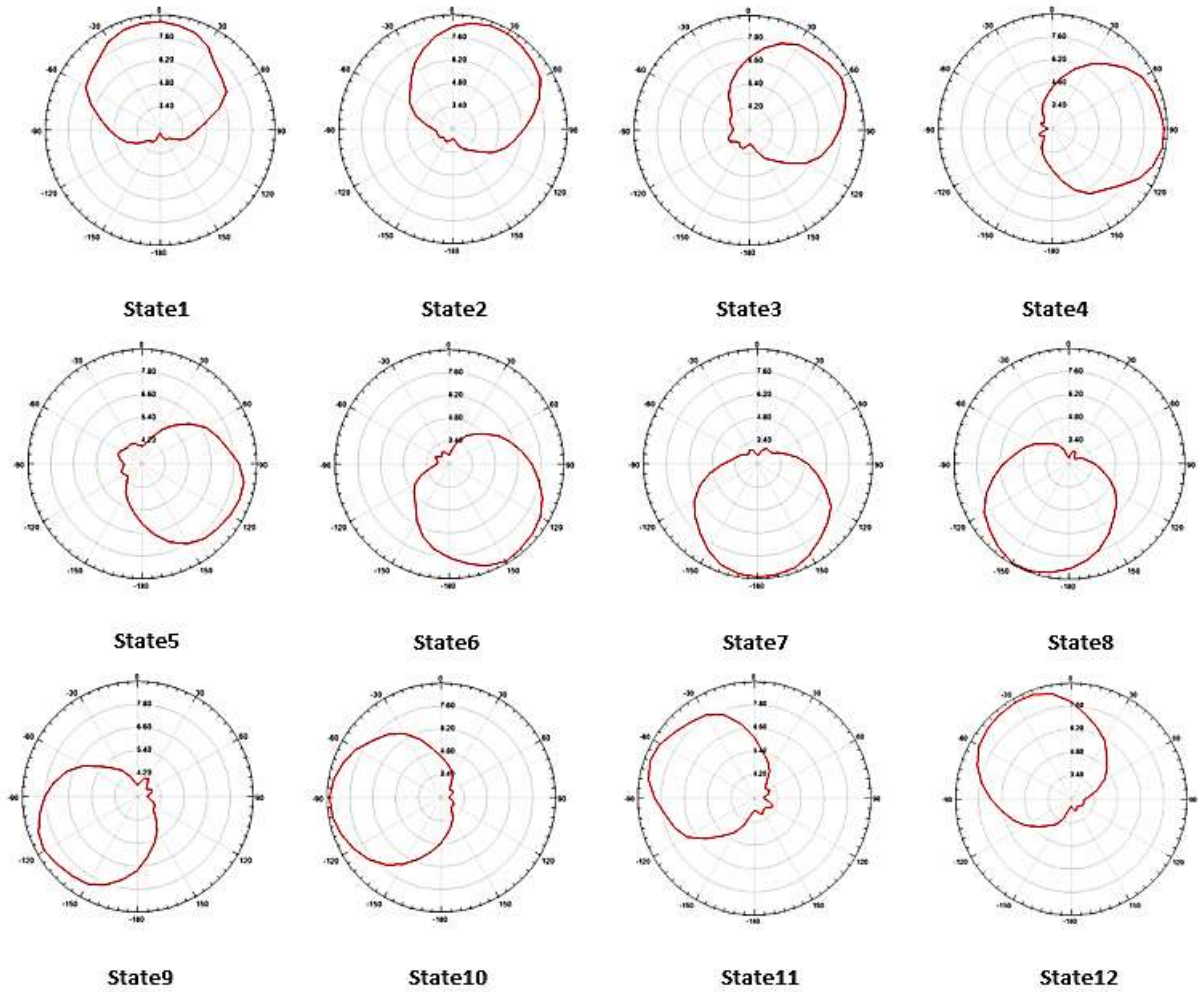
Operation state	Pin diodes						Beam Direction (°)	Bandwith (GHz)	Gain (dB)
	D1	D2	D3	D4	D5	D6			
State1	1	0	0	0	0	0	0	55,29 _ 63,26	7.99
State2	1	1	0	0	0	0	30	57,9 _ 63,63	7.56
State3	0	1	0	0	0	0	60	59.14 _ 63.80	7.15
State4	0	1	1	0	0	0	90	57.78 _ 63.70	7.54
State5	0	0	1	0	0	0	120	59.50 _ 63.87	6.94
State6	0	0	1	1	0	0	150	55,36 _ 63,29	7.99
State7	0	0	0	1	0	0	180	59.33 _ 63.86	6.83
State8	0	0	0	1	1	0	210	57.79 _ 63.57	7.63
State9	0	0	0	0	1	0	240	59.08 _ 63.81	7.10
State 10	0	0	0	0	1	1	270	57.90 _ 63.70	7.53
State11	0	0	0	0	0	1	300	59.20 _ 63.90	7.13
State12	1	0	0	0	0	1	330	55.02 _ 63.00	8.10

**Table III.2:** Operation modes and their corresponding angles

The operation states	State1	State2	State3	State4	State5	State6
The angle	0°	30°	60°	90°	120°	150°
The operation states	State7	State8	State9	State10	State11	State12
The angle	180°	210°	240°	270°	300°	330°

### III.3.8 Critical Analysis

The simultaneous result of return loss ( $S_{11}$ ) for all the states is less than -20 dB at the resonance frequency 60GHz. The radiation pattern is directional and it can be automatically controlled and directed to radiate in the desired angle in the azimuth plane from 0° to 330° by applying the corresponding PIN diode configuration, with a wide bandwidth that reaches to more than 8 GHz. Moreover, analyzing the other antenna characteristics, it has shown that the antenna a good impedance matching, high efficiency, and a low frequency sweep in terms of the resonance frequency and the difference in bandwidth between different PIN diode configurations is not too large.



**Figure III.6:** Radiation pattern in different states from 1 to 12.

### III.4 Conclusion

In this chapter, we presented the obtained results from the simulation of the design of a reconfigurable radiation pattern printed antenna using HFSS. Simple six PIN diodes have been used to switch from one direction to another. It can cover a wide band from 55 to 64 GHz depending on diode states. The antenna has a broad bandwidth where the difference in bandwidth between different PIN diode configurations is not too large. The antenna has a good impedance matching at the resonant frequencies, with a peak gain that reaches 8.10 dB, and high efficiency within the operating band. Although being one of the smallest antennas of its type, it covers a wide band. Such a small size wideband reconfigurable antenna will be suitable for 5G hand-held devices, this design can be used for many other 60 GHz spectrum applications.

# **GENERAL CONCLUSION**

## General Conclusion

In this dissertation, a new design for pattern-reconfigurable antenna loaded has been presented for 60 GHz mmWave applications. We have studied the design problems of reconfigurable antennas which have received a lot of attention these decades especially in the field of future wireless communications. Indeed, these reconfigurable antennas offer the possibility of switching between its functionalities using active components such as PIN diodes.

Reviewing the various types of reconfigurable antenna, several design techniques are discussed in detail, and the fundamental properties of the reconfigurable antenna are set out. The complexity of an antenna increases with the number of reconfigurable parameters is clearly stressed in this review. Besides, the presentation highlights a design requirement, the ability to design an antenna with simultaneous and independently flexible reconfigurations of the antenna radiation pattern.

The objective of our work was the design of a reconfigurable antenna in a radiation pattern dedicated to millimeter-wave applications. To achieve this goal, a parametric study was applied using the HFSS 3D electromagnetic simulation software at a high resonance frequency (60GHz). The software is used to model the PIN diodes (packages) in the two ON / OFF states under the design studio interface.

During this work, we developed a reconfigurable antenna from a simple rectangular patch antenna using an in-depth parametric study which allowed us to get a great idea on the effect of each parameter on the characteristics of antennas such as the reflection coefficient, radiation pattern, and bandwidth. We optimized the parameters of the antenna until reaching the final satisfying and high performances for the proposed antenna.

However, this reconfigurable antenna is designed to be integrated with much architecture to develop patterns for the current and future millimeter applications system. Utilizing six PIN diodes to cover all the directions in the azimuth plane and new fabrication techniques for the antennas represent another approach to offer multiple prospects for the system performance. This will make mm-wave an even more viable alternative to the conventional low-gain resonant antenna. Although being one of the smallest antennas of its type, it covers a wide band. Such a small size wideband reconfigurable antenna will be suitable for 5G hand-held devices, this design can be used for many other application of the 60 GHz spectrum.

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