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MINISTRY OF HIGHER EDUCATION AND SCIENTIFIC RESEARCH

جـــــــــــــامعة سعيدة – د. الطاهر مولاي –

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Faculty of Technology

A Dissertation Submitted to the Department of Telecommunications in Partial Fulfillment of the Requirements for Degree of Master of Systems of Telecommunications;

Presented by: Miss. ATBI Fadoua Ines

Miss. YAHIAOUI Manel

A miniature Antennas design based on metamaterial concepts for Radio Frequency Identification (RFID) Application

Defended on June, 20, 2024 in front of the jury composed of:

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Dedication

*I dedicate this work and i would like to thank to my mother, **Chaalane Nedjma**, and my father, **Djillali**, my sisters and my brother for their unwavering support and for always believing in me. Their encouragement has been my refuge and motivation throughout my academic career, and to my friend and confidant**, Atbi Ines Fadoua**, for being here. This work could not have been done without you.*

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ATBI Fadoua Ines

"This memoir is the fruit of a collective as much as a personal effort, and I am deeply grateful to all those who have accompanied me."

ABSTRACT

RFID (Radio Frequency Identification) is a very good candidate for contactless identification and tracking systems and thus finds applications in several areas: distribution, production, logistics, security, stock inventory, surveillance, etc. An RFID system is mainly composed of a reader communicating with one or more tags. Antennas are key elements of readers and tags, and their performance directly affects the overall performance of the RFID system (range, probability of detection, cost, size, etc.).

The main objective of this work is to explore solutions to the problems of miniaturization and performance degradation, thus contributing to the advance of RFID technology. This work is focused on the antenna design working at the UHF frequency band (800–950 MHz), exploring alternative techniques based on folded meander-line as radiating elements and also the use of new DGS-metamaterial resonators (complementary double-rings hexagonal resonators) etched into the ground plane. The performance of miniaturized antenna designs is achieved and improved in terms of gain, radiation patterns and reflection coefficients using HFSS software.

Keywords: Design, simulation, miniaturization, microstrip antenna, RFID, performance, meander-line, metamaterial, resonator, HFSS.

Résumé

RFID (Identification par Radiofréquence) est un très bon candidat pour les systèmes d'identification et de suivi sans contact et trouve donc des applications dans plusieurs domaines: distribution, production, logistique, sécurité, inventaire des stocks, surveillance, etc. Un système RFID est principalement composé d'un lecteur communiquant avec une ou plusieurs tags. Les antennes sont des éléments clés des lecteurs et des tags, et leur performance affecte directement les performances globales du système RFID (portée, probabilité de détection, coût, taille, etc.).

L'objectif principal de ce travail est d'explorer des solutions aux problèmes de miniaturisation et de dégradation des performances, contribuant ainsi à l'avancement de la technologie RFID. Ce travail est axé sur la conception de l'antenne fonctionnant dans la bande de fréquence UHF

(800–950 MHz), l'exploration de techniques alternatives basées sur la ligne de meander pliée comme éléments rayonnants et aussi l'utilisation de nouveaux résonateurs métamatériaux DGS (résonateurs complémentaires hexagonaux à double anneau) gravés dans le plan du masse. La performance des conceptions d'antennes miniaturisées est obtenue et améliorée en termes de gain, de rayonnement et de coefficients de réflexion en utilisant le logiciel HFSS.

Mots-clés : Conception, simulation, miniaturisation, antenne microruban, RFID, performance, ligne de méandre, métamatériau, résonateur, HFSS.

ملخص

RFID (تحديد الهوية بالترددات الراديوية) هو مرشح جيد جدًا لأنظمة التعرف والتتبع بدون تلامس وبالتالي يجد تطبيقات ف
ي عدة مجالات: التوزيع والإنتاج والخدمات اللوجستية والأمن وجرد المخزون والمراقبة وغيرها. يتألف نظام أساسًا من قا
رئ يتواصل مع بطاقة أو أكثر. الهوائيات هي عناصر رئيسية في القارئات و البطاقات ، وأداؤها يؤثر مباشرة على الأداء ال
عام لنظام RFID (المدى، واحتمال الكشف، والتكلفة، والحجم، إلخ).
الهدف الرئيسي لهذا العمل هو استكشاف حلول لمشاكل التصغير وتدهور الأداء، مما يسهم في تقدم تكنولوجيا RFID.يرك
ز هذا العمل على تصميم الهوائيات التي تعمل في نطاق الترددات فوق العالية (800-950 ميجاهرتز)، باستكشاف تقنيات بد
يلة تعتمد على الخط المتعرج المطوي كعناصر مشعة وأيضًا استخدام مرنانات المواد الاصطناعية DGS الجديدة (الرنانا
ت التكميلية السداسية المزدوجة الحلقة) المحفورة في المستوى الأرضي. يتم تحقيق أداء تصاميم الهوائيات المصغرة وتحسي
نها من حيث الكسب وأنماط الإشعاع ومعاملات الانعكاس باستخدام برنامجHFSS .

الكلمات المفتاحية: تصميم، محاكاة، تصغير، هوائي متناهي الصغر، RFID, ، أداء، خط التعرج، مادة خارقة، مرنان، HFSS.

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Chapter III : Design, simulation and realization

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List of abbreviations:

RFID	Radio Frequency Identification
AIDC	Automatic Identification and Data Capture
IFF	Identify Friend or Foe
IBM	International Business Machines.
PDA	Personal Digital Assistant
IC	integrated circuit
HF	High-frequency
UHF	ultra-high-frequency
LF	Low frequency
PVC	polyvinyl chloride
RTLS	real-time location systems
SHF	Super High Frequency.
ISO	International Organisation for Standardization
IEC	International Electrotechnical Commission
RTF	Reader Talk First
TTF	Tag Talk First
HDX	half-duplex
HPBW	Half-Power Beam Width
FNBW	First-Null Beamwidth
VSWR	Voltage Standing Wave Ratio
SWR	Standing Wave Ratio
IFA	Inverted-F Antenna
MIFA	Monopole Inverted-F Antenna
PIFA	Planar Inverted-F Antenna
HFSS	High Frequency Structure Simulator.
CPMPAs	circularly polarized microstrip patch antennas
PCBs	Printed Circuit Boards

MTM	Metamaterial
DPS	Double-positive
ENG	Epsilon-negative
MNG	MU-negative
DNG	Double-negative
SRR	Split Ring Resonator
NIM	Negative refractive index material
EM	Electromagnetic
NRW	Nicolson Ross Weir
SRR	Split Ring Resonator
FEM	Finite Element Method.
DGS	Defected Ground Structure
PMC	Perfect Magnetic Conductor
PEC	Perfect Electric Conductor
CRHCR	Complementary double-ring hexagonal closed resonator
RHCR	Double-ring hexagonal closed resonator

General introduction

In the last years, radio frequency identification technology (RFID) have become very popular due to its exponential growing applications in many fields like, manufacturing companies, logistics, distribution, goods, flow systems, electronic toll collection, retail item management, asset identification, animal tracking, access control, and vehicle security [1]-[2].

The RFID is a technology used to track and identify objects of all types, including humans and animals, by radio waves data capture [3]-[4].

The RFID systems distinguish from each other by system usage, operating frequency, reading distance, protocol, power transfer to the tag, the procedure for sending data from the tag to the reader, and so on [5]. Depending on the application, RFID systems operates at different frequencies, UHF identification technology has gained a lot of attention due to its longer range and higher data transfer rate, compared to LF and HF [6]. The UHF-RFID band is between 860 - 960 MHz defined by ITU (International Telecommunication Union), but each country has its own allocated frequency range.

A basic RFID system consists of RFID tag, RFID reader, computer host and communication network [6]. The RFID tag is the most relevant component in this system because it greatly impacts on the whole system. A typical RFID tag consists of an antenna and a microchip with internal read/write memory. The reader is a device that communicates with the transponder through an antenna; it can read and write information on the RFID chip [7]-[8].

Antennas are a very important factor in communication between reader and tag in RFID systems. Low cost, high performance, compact size, wideband, and low profile antennas often meet the stringent requirements of modern wireless RF communication systems. The design of a RFID tag requires compact antennas; however, it is very difficult to design antennas with good performance and small size at the same time.

Many techniques such as metamaterial, defected ground structure (DGS), the use of slot, folding techniques, and fractal methods are used for size reduction and antenna performances enhancement [8]-[9]-[10].

Metamaterials are artificial material which have unique natural features, their electromagnetic characteristics theoretically proposed by Veselago in 1968 [11] typically attract considerable attention in the scientific community.

This material is one of the many new technologies being adopted to improve the performance of radio frequency identification (RFID) systems. In particular, metamaterial-based antenna designs are being used more frequently to improve the read range and reduce the size of passive UHF RFID tags [12].

This memory makes a contribution to the optimization and reduction of RFID antenna dimensions using certain techniques for miniaturizing antennas. The essential contribution of this study aimed to design microstrip antennas while considering both the simplicity and effectiveness of the design process. The microstrip antennas are usable because they have low-profile planar configuration, compatibility with Integrated Circuits (IC), and low fabrication cost. Complementary metamaterial resonators are used in this process of miniaturization of microstrip antennas. The performance of the proposed antenna was analyzed in terms of gain and return loss through simulations with HFSS software.

This Dissertation is divided into three chapters organized as follows:

First chapter: Provides a detailed definition and history of RFID technology and its applications, focusing on the passive UHF architecture. A study was conducted to classify existing RFID systems into classes (passive, semi-passive and active) and bands (LF, HF and UHF). In this chapter, different coupling mechanisms (communication links) have been discussed. At the end of this chapter, different coupling mechanisms (communication links) were discussed.

Second chapter: Is divided into two parts: the first recalls the different properties and characteristics of antennas, while the second presents the different antennas used on RFID, in addition to techniques for adapting and miniaturizing RFID antennas. These techniques show that there are several ways to reduce the dimensions of antennas.

The third chapter: Dedicated to the design and manufacture of UHF RFID antennas, in which we present our proposed antennas.

Our work is finish with conclusion and proposing perspectives as a future works.

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Chapter I
RFID Technology

I.1 Introduction :

In this chapter, we briefly discuss the concept of automatic identification, which operates Radio Frequency Identification (RFID) technology.

The chapter begins by giving the history of technology RFID, the components of system and the principle of operation. Then, the various classifications of this system and the fields of application related to this technology are detailed. Finally, This chapter describes standards for using RFID technology.

I.2 RFID Technology:

RFID (Radio Frequency Identification) is a technology that belongs to a group of technologies referred to as Automatic Identification and Data Capture (AIDC). AIDC methods automatically recognize and identify objects, shapes, or individuals from a distance (ranging from contact to several meters).

RFID systems consist of three essential elements: RFID tags, which are tiny devices that store data; RFID readers, which wirelessly communicate with the tags; and a back-end system, which manages and processes the collected information (Figure I.1).

Radio frequency technology is commonly used to transmit and receive information wirelessly. A wide variety of electronic devices, such as televisions, radios, and cell phones, use this principle to transmit or receive information. The transmitter continuously emits radio-frequency radiation, supplying both energy (for passive tags) to the tag in electromagnetic form and the information to be transmitted. The tag then reacts, utilizing the energy it contains to send the information back to the receiver. In contrast to barcode technology, which is read by an optical laser, an RFID reader scans or interrogates a tag using radio-frequency signals. RFID is a wireless communication technology that uses radio waves to automatically identify tagged objects or things [1].

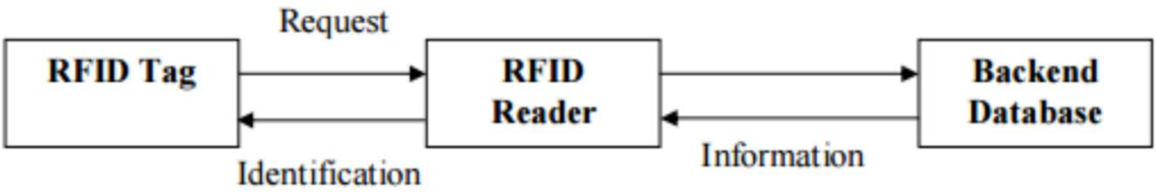

Figure I.1: Basic building blocks of an RFID system [1].

I.3 History:

The first principle of RFID technology has been applied during the Second World War and is directly related to the development of radio propagation and the radar system [2]. To identify / authenticate flying machines in British airspace, allies put transponders in their aircraft to answer interrogations of their radars. This system, known as IFF ‘Identify Friend or Foe’ represents the first use of RFID [3]. Today, air traffic control remains based on this principle. The RFID was first studied by Harry Stockman in 1948 [4], followed in particular by the works of F. L. Vernon [5], and those of D.B. Harris [5], who are considered the founders of this technology.

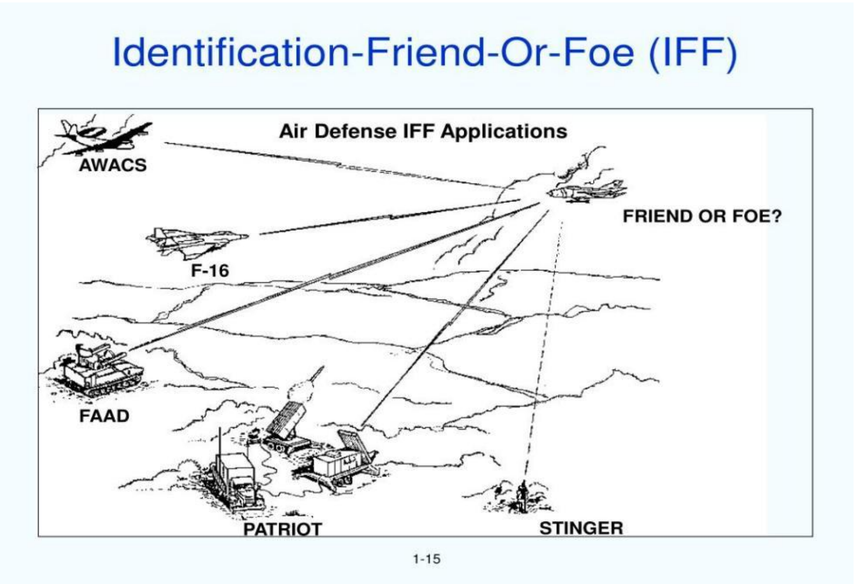

Figure I.2: IFF System (Identify Friend or Foe) [6].

RFID Technology

The first patent related to RFID technology was filed in the United States by Mario Cardullo in 1969 for the identification of locomotives [3]. RFID systems during the years 1969 and 1979 remain restricted, mainly for military use for controlling access to sensitive sites, such as the nuclear sector. At the end of the 1970s technology spread to the private sector. The identification of livestock in Europe remains one of the first commercial applications. This is followed by numerous uses in the same field particularly in the car manufacturers' production lines. By the early 1980s, RFID tags began to be manufactured by several European and American companies. Technological advances allow the appearance of the passive tag receiving its energy by the signal of the reader [3]. This feature makes the tag less expensive because it allows the absence of on-board power source, and reading distances are a few centimeters. In the 1990s, it is the beginning of standardization for easy interaction of RFID equipment to accept the services of other systems. In addition, the miniaturization of the RFID system allows its integration into a single chip by International Business Machines (IBM) [3].
As early as World II, RFID has evolved significantly. It has become a necessity in the supply chain of many enterprises around the globe.

The following graph illustrates the evolution of this technology over time.

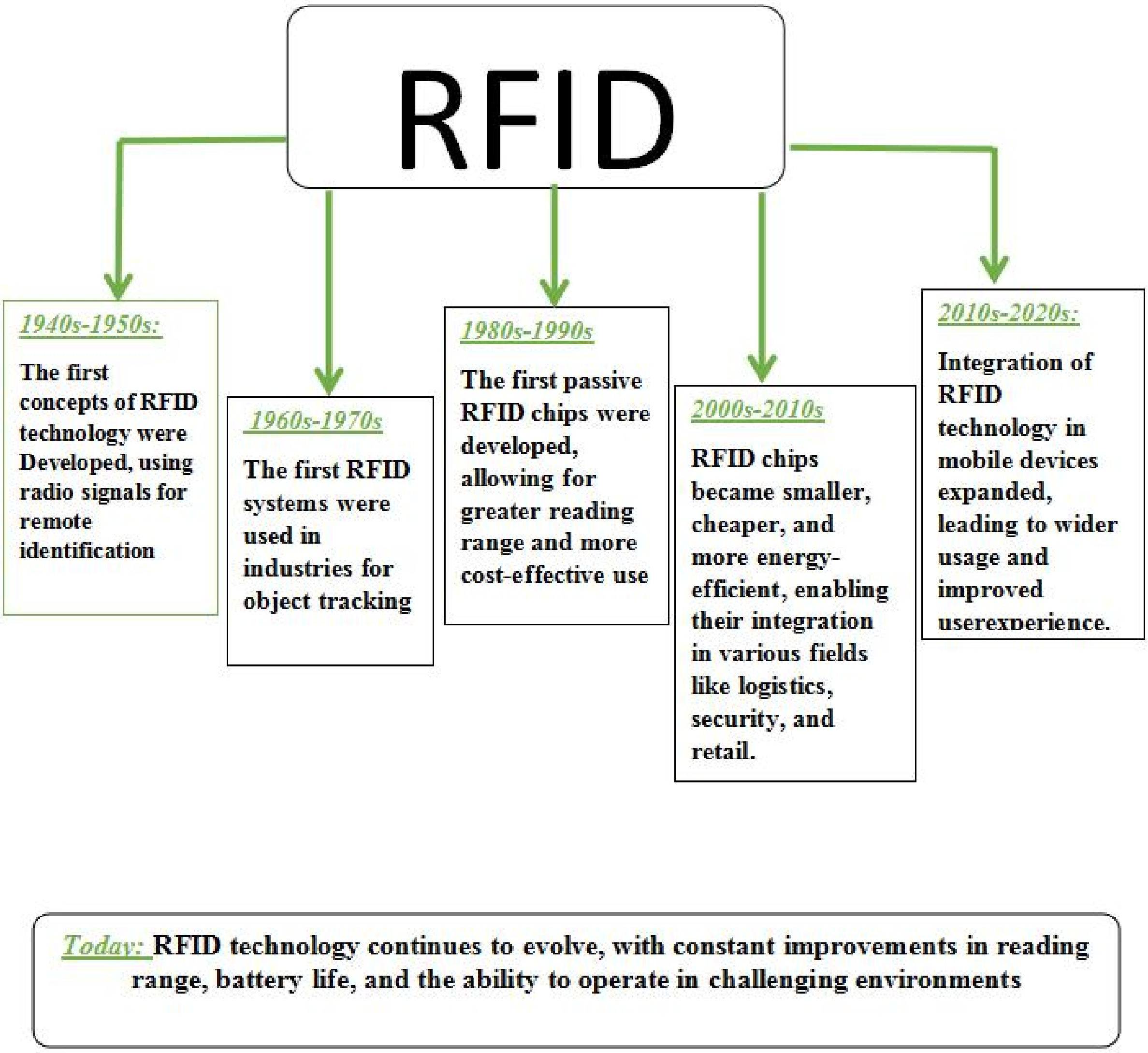

Figure I.3: The evolution of RFID technology over time.

I.4 RFID Applications and Domains:

RFID technology is widely used in several commercial and industrial applications to search, identify, track and communicate with various objects, people, items or things. Some common uses of RFID technology are as follows (Figure I.4):

Figure I.4: Application areas for RFID technology.

I.4.1 Healthcare Applications:

RFID technology is less well known in the health sector. However, it allows many advances in the location of patients, the security provided by medical traceability, the monitoring of processes, and the quality of care of patients [5]. This technology offers axes of development for the identification, the authentication, the geo-localization of materials and patients, the security of the follow-up of the patients as well as for the traceability of the health products from the pharmacy to the patient's room. In some hospitals and clinics, emergency department patients are equipped with an RFID wristband that allows doctors and healthcare personnel with a tablet PC to know in real time the data related to each patient (Figure I.5).

Figure I.5: RFID technology in Healthcare [7].

I.4.2 Security & Control Applications:

RFID tags can be attached to the equipment/user personal/official belongings such as organization ID cards and vehicles (Figure I.6). By applying RFID technology in secure zones not only permission can be granted to and revoke for the users/persons in particular zone but also record individual access and the length of their stay. It is also good for audit trial. These types of application consider time and flow carefully and as an aspect that is very important.

Figure I.6: RFID Access control [8].

I.4.3 RFID Vehicle Tracking System:

RFID is a wireless technology that uses radio waves to identify a person or object. In RFID-based vehicle tracking system, vehicles are equipped with unique RFID tags namely RFID windshield tags. These tags are encoded with vehicle-relevant data such as vehicle owner's name, license no, vehicle model, digital wallet integration, etc. When vehicles affixed with RFID tags pass by one of these RFID reader-enabled premises, the reader scans the encoded data from the tags with the help of RFID antennas. The data thus captured about the vehicles is transmitted to a central vehicle tracking database system for tracking and analysis purposes.

RFID vehicle tracking system is beneficial in various industries including fleet management, access control, supply chains, warehouse management.

Figure I.7: RFID Vehicle application [9].

I.4.4 Baggage Applications:

Airline industries, package and delivery service lose a lot of money on lost or late delivery of baggage/packages [12]. Handling large amount of packages from many places to various destinations on different routes can be very complex. In this scenario RFID application provide best resource management, effective operation and efficient transfer of packages. RFID helps to identify the packages, and provide records that can advice the industry on possible areas that may require some improvements. It also keeps customers informed about their packages.

Figure I.8: RFID Technology for Baggage Tracking at airports [10].

I.4.5 RFID as a Payment Tool:

As a payment tool, RFID technology has been used as a closed payment system that only works in the specific operational frequency range. Contactless smart cards and transponders can only be used to purchase goods or services from a particular supplier [11]. Among the RFID applications in this field, the Pidion BIP-1300 model (Figure I.9) is a PDA (Personal Digital Assistant) device that supports chip, magnetic stripe or contactless payments. Through RFID wristbands, customers have access to convenient payment features. These are mainly prepaid systems, which mean that the card must be charged to a charging terminal with money, credited on the chip card and then debited at the provider's cash desk. Because closed systems are tailored to the needs of the system vendor, wide varieties of RFID standards and data structures are used.

Figure I.9: BIP-1300 Barcode Scanner [13].

I.4.6 Animal Identification:

This is one of earliest RFID application. RFID tag can be injected to remain under skin of animal. This process is less painful and there is no identification mark with the help of which tag can be removing or modify. RFID chip inside tag is Read-only so data cannot be modified. This chip contain many information like date of birth, last vaccination done, any medical history and distinguishing features about the animal(Figure I.10).

Figure I.10: RFID for Animals.[14].

I.4.7 National Identification:

National identification has been a biggest problem for all the countries. However, now for identification, RFID technology can be used. A user has only a single card with embedded RFID chip. This RFID tag number then points to an online database which is accessed by multiple agencies. A single ID card needs to be issued for identification.

Figure I.11: RFID National identification [15].

I.5 Operating Principle of an RFID system:

This technology is based on the use of electromagnetic waves, whether to provide power to the tags or for the exchange of data between the reader and the tags, once the information has been transmitted to the RFID reader equipped with an antenna, All that's left to do is convert the radio waves into data that must be interpreted by software.

So an RFID application basically consists of three elements so that the communication is established, a reader that transmits a signal at a frequency determined to one or more radio tags located in its field of reference (Figure I.12). Operation and data processing system (it is an infrastructure computer information technology that is used to collect and use the data).

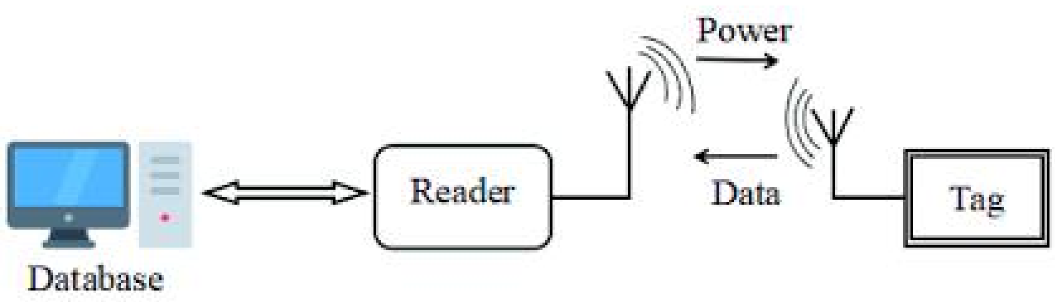

Figure I.12: Principle design of RFID technology [16].

I.6.Components of RFID Technology:

An RFID system, as shown in (Figure I.13), is composed primarily of three elements necessary for its operation.

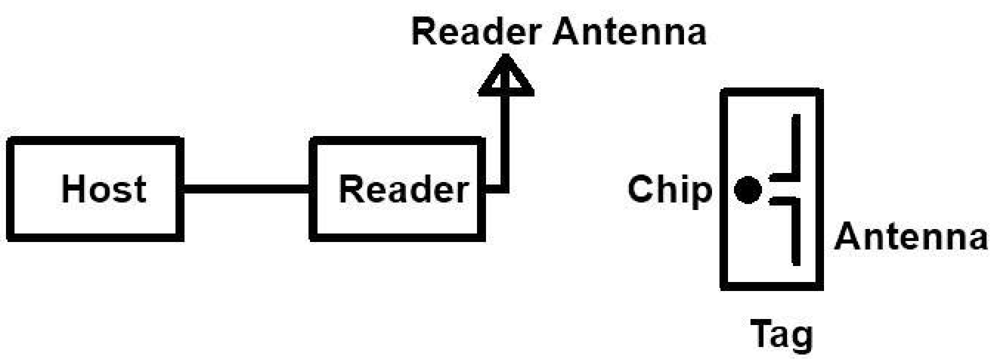

Figure 1.13: The main elements of an RFID system [17].

I.6.1 RFID tag:

These are receiving devices, which are placed on the items to be identified (object, animal...). They are fitted with a chip containing the information and an antenna to enable exchange information with the reader also the RFID tag is an electronic circuit comprising a chip and an antenna that responds to commands issued by the reader (Figure I.14). There are two categories: active and passive. The active tag supplies its own energy via a battery, while the passive tag converts the received signal into energy and uses it to transmit.

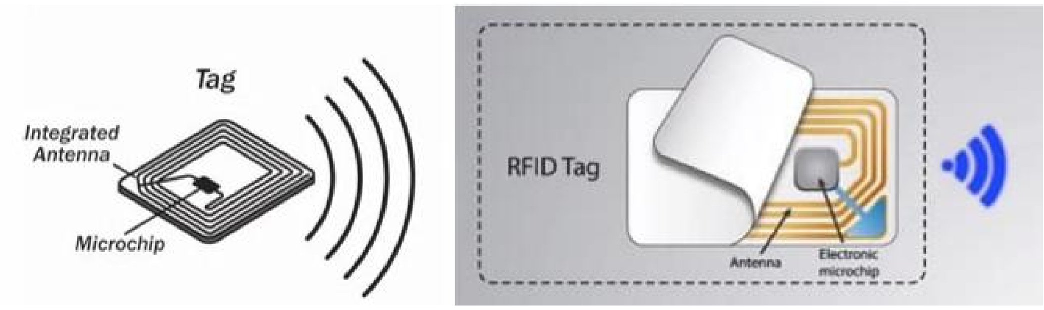

Figure I.14: RFID Tag [18].

And it comes in many forms (Figure I.15)

Figure I.15: Shapes of RFID Tag [19].

I.6.1-a Physical structure of tag:

Regardless of its type, an RFID tag consists of three primary components: the RFID chip or integrated circuit (IC), the antenna, and the substrate.

- Microchip:

The RFID microchip is essentially the ‘brain’ of the tag. The microchip stores the unique identification information for the object to which the tag is attached. The average storage range of an RFID microchip is 64 bits to 2 kilobytes. However, some chips also have additional memory for storing further data about the item.

Furthermore, the chip is responsible for receiving and processing signals from the RFID reader.

-Antenna:

The antenna is a crucial component of an RFID (Radio Frequency Identification) tag. It’s designed to receive and transmit signals from an RFID reader.

The size, shape, and type of the RFID antenna can vary widely depending on the application, frequency of operation, and the level of performance required.

Most commonly, RFID antennas are made of a small coil of wires, with the number of turns in the coil and the material of the wire affecting the tag’s range and sensitivity.

There are different types of antennas used in RFID tags, such as dipole, loop, slot, and patch antennas, each with its unique characteristics and advantages.

For example, dipole antennas are often used in high-frequency (HF) RFID systems.

Dipole antennas are composed of two metal rods or wires connected to the tag's circuit and have a bidirectional radiation pattern with linear polarization. Loop antennas are circular or rectangular antennas with one or more turns of wire or metal strip connected to the tag's circuit they have a unidirectional radiation pattern with circular polarization. Patch antennas are flat and rectangular antennas composed of a metal patch on a dielectric substrate connected to the tag's circuit, featuring a unidirectional radiation pattern with linear polarization. Dipole antennas are suitable for low-frequency and high-frequency tags, while loop antennas are suitable for high-frequency and ultra-high-frequency tags. Patch antennas are ideal for ultra-high-frequency and microwave tags due to their thin and compact form.

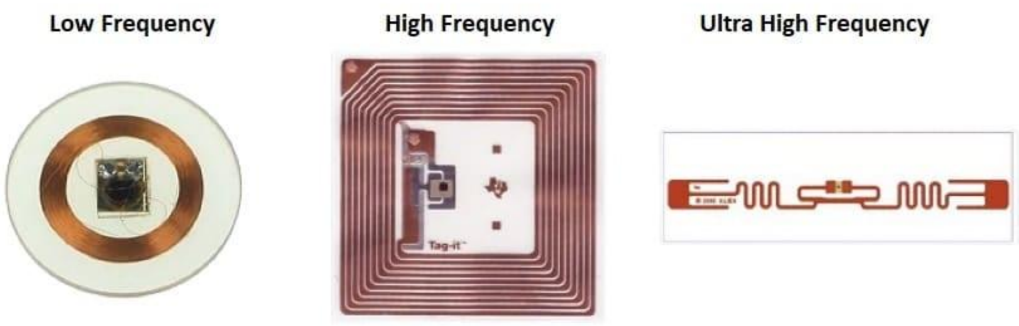

Figure I.16: Antenna Tag for different frequency bands [20].

- Substrate:

The substrate serves as the 'body' or foundation of the RFID tag. It is the material onto which the chip and antenna are mounted.

The substrate is designed to withstand various environmental conditions like heat, moisture, vibration, chemicals, sunlight, and abrasion that the RFID tag may encounter throughout its lifecycle. The substrate material is chosen to be resilient and capable of withstanding these conditions, ensuring that the tag remains functional and intact.

In some cases, a protective layer is added to the substrate to securely attach the RFID tag to an object. This protective layer can be made of materials like PVC lamination, epoxy resin, or adhesive paper. The protective layer provides additional protection to the tag, ensuring it remains securely affixed to the object and preventing damage from external influences.

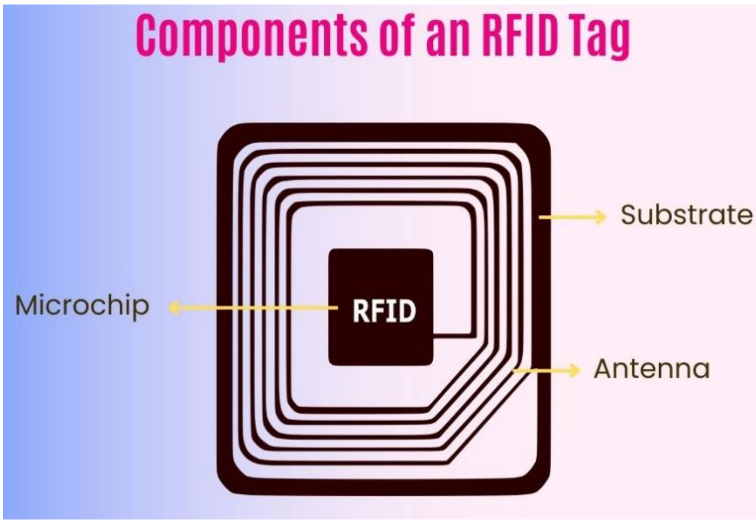

Figure I.17: Components of an RFID tag [21].

I.6.1-b.Types of tag:

RFID tags can be divided into three categories based on their power source:

-Passive RFID Tags:

Passive RFID tags do not have a built-in power source. Instead, they draw power from the radio waves of an RFID reader. The RFID reader emits these radio waves, energizing the passive RFID tag, which transmits its data to the reader.

The operating range of passive tags varies according to their frequency.

Low-frequency (LF) and high-frequency (HF) tags have a maximum range of about 10 cm and 1 meter, respectively. In contrast, ultra-high-frequency (UHF) passive RFID tags can work up to a range of 12 meters under optimal conditions.

Passive tags are widely utilized due to their small size (about 1/10th the size of other HF tags) and cost-effectiveness. They find applications in diverse sectors such as access control, file tracking, race timing, supply chain management, and smart labels, among others.

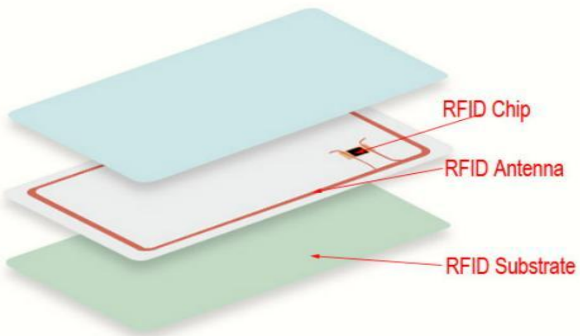

Figure I.18: An example of a passive UHF RFID tag [22].

-Active RFID Tags:

Unlike passive tags, an active RFID tag possesses their own power source, typically a battery, enabling them to broadcast their signal.

Because of their extended range and larger memory capacity, active tags are commonly used in scenarios where items need to be tracked over a longer distance. Examples include tracking high-value assets in large warehouses, vehicle tracking in transportation, and real-time location systems (RTLS) in healthcare settings.

Although active tags are essential for applications that require longer read ranges, they are also vulnerable to radio intrusion and noise interference. The size, weight and price of active tags are more comprehensive than other tags. Another disadvantage of active tags is that their life duration is less than passive and semi-passive tags.

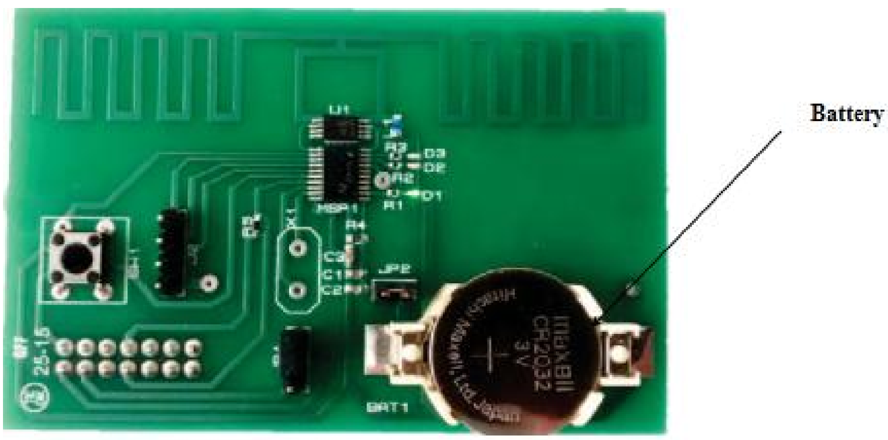

Figure I.19: Active Tag [23].

-Semi-active RFID Tags:

These tags are, of course, halfway between the two technologies mentioned above. The label has its own energy source but requires a reader to transmit the data it contains. The advantage of this technology over a passive tag is that it can be read much more quickly and, above all, from a greater distance.

Semi-active tags are particularly useful in situations where a longer read range than passive tags is needed but where active tags might be too costly or bulky. This includes tracking shipping containers in logistics, temperature monitoring in cold chain logistics, and asset tracking in large facilities.

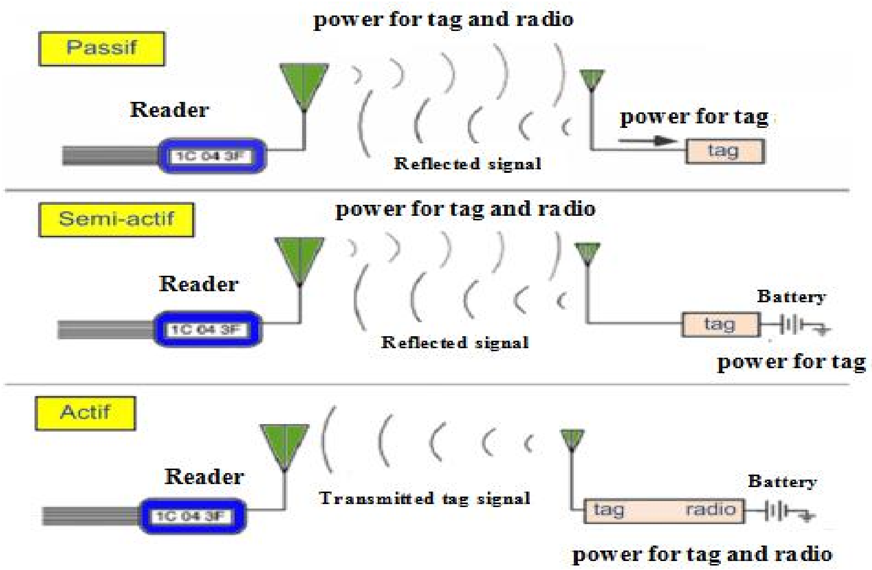

Figure I.20: Tag types and power supply [24].

I.6.2 RFID Reader:

RFID is the most significant hardware component in RFID technology and acts as the brain of the system. It transmits and receives radio waves for communication with the RFID tag or transponder. It is connected to the antenna and receives data from the RFID tag. It also converts received radio waves into digital data on a computer database.

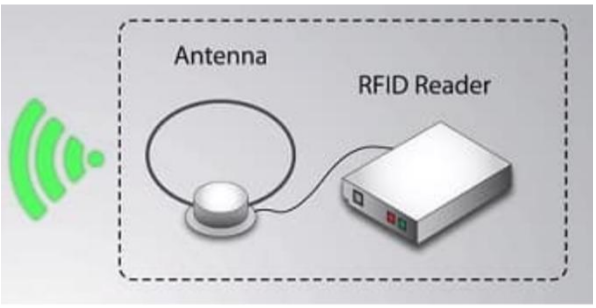

Figure I.21: RFID readers [25].

RFID readers come in a variety of shapes and sizes, and they can be handheld, desktop, or mounted (Figure I.22). Some RFID readers also have integrated printers that can print out information from the tags, while others have displays that show tag data in real-time.

Regardless of their form, all RFID readers serve the same basic function: to collect data from tags so that it can be used for various purposes.

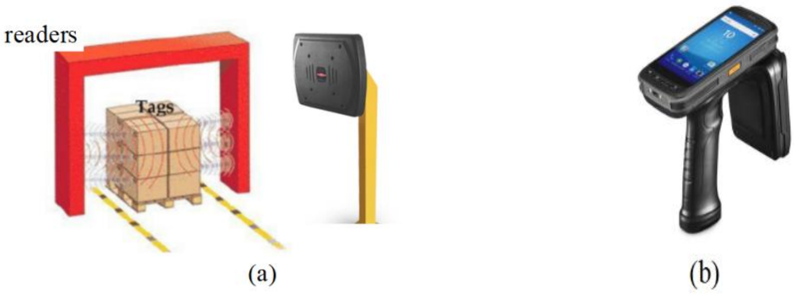

Figure I.22: **(a)**-Fixed -**(b)** mobile RFID readers [26].

- Specification of RFID Reader:

Operating frequency is one of the specifications of the RFID reader.

Different types of RFID systems operate at different radio frequency as given in table I.1. Each radio frequency has its own read distance, power requirements and performance.

The choice of frequency depends on the application. Mostly four types of frequencies are used in RFID technology:

A. Low frequency (120-140 KHz):

Low frequency RFID reader operates in low frequency range. Low frequency tags are used for depositing and with draw and controlling following with the assets.

B. High frequency (13.56 MHz):

High frequency RFID reader operates in high frequency range. HF readers are useful for asset-tracking applications, contact-less credit cards and ID badges.

C. The ultra-high frequency (800 MHz-950 MHz):

UHF RFID reader operates in UHF tags are used in supply chain management applications.UHF readers offers the longer reading range and are cheaper to manufacture in bulk

D. Microwave (2.4 GHz-5.8 GHz):

Microwave system offers higher read rate. Microwave readers are expensive than UHF readers. Microwave readers are used in electronic toll applications.

Frequency range	Frequencies	Passive read distance
Low frequency « LF»	120 & 140 KHz	10 – 20 cm
High frequency « HF»	13.56 MHz	10 – 20 cm
Ultra High Frequency « UHF»	800 & 950 MHz	3 meters
Microware « SHF»	2.45 & 5.8 GHz	3 meters

Table I.1: RFID operating frequency [26].

I.6.3 Software:

The software controls the reader and tags in RFID technology.This technology uses specific types of software programs for RFID operations. The software controls the reader, scanning, and information retrieval from tags. It is used to store data and information on a local computer or to forward it to cloud storage.

RFID software typically includes a database, an application server, and a user interface. The database stores information about the objects being tracked. The application server processes information from the other RFID system components and updates the database accordingly. The user interface allows users to view information about the objects being tracked and perform various operations on them.

I.6.4 Radio Frequency Identification (RFID) Middleware:

This is the RFID software, which sits between the readers and the enterprise's business applications. The middleware software has numerous purposes and plays a major role in RFID system management and operation. The middleware software does not merely manage the RFID printers and readers and connects between these devices and the business applications; likewise, it filters, manages, aggregates, and makes sense of the information coming from the RFID tags. Due to the complete volume of information coming from the RFID tags, if for example, thousands of RFID tags are read at almost the same time thousands of times, RFID systems need a new kind of middleware as well as unadventurous addition middleware. Orthodox middleware is used mainly to link distinct applications, both externally and internally, and to the enterprise for: decoding information into different formats Web services Routing data using different transport protocols.

1.7 RFID System Standards:

The interoperability of RFID equipment (readers and tags) requires standardization in terms of how they operate. For a given frequency of use, any tag must be read by any reader. This is the definition of the air-interface communication protocol. ISO (International Organization for Standardization) and IEC (International Electrotechnical Commission) are organizations that set operating standards for different technologies [27]. They work together in particular for all standardizations concerning information technologies.

ISO/IEC has drafted standards for the identification and management of objects or equipment in the ISO 18000 series of interface protocols designed for logistics. These standards cover the entire range of frequencies used worldwide for RFID. Table I.2 groups the various standards together. It should be noted that the ISO/IEC 18000-5 standard for operation at 5.8 GHz has been abandoned due to a lack of consensus.

standards	Objective
ISO/IEC18000-1	General architecture and parameters to be standardized
ISO/IEC 18000-2	Parameters for air interface communications up 125 KHz
ISO/IEC 18000-3	Parameters for air interface communications at 13,56 MHz
ISO/IEC 18000-4	Parameters for air interface communications at 2,45 GHz
ISO/IEC 18000-6	Parameters for air interface communications between 0,86-0,96 GHz
ISO/IEC 18000-7	Parameters for air interface cosmmunications at 0,433 GHz

Table I.2: ISO/IEC standards governing the operation of RFID [27].

I.8 -The Mechanism of RFID Technology:

The working of RFID technology is based on the principle of inductive coupling, including a source antenna and a receiver antenna. As we know, each RFID tag has a microchip containing a unique identification number, model, manufacturing date, expiry date, access information, short description, etc.. The RFID reader accesses such information.

The operation of the RFID process starts with the scanning of an object or item during scanning, tags are placed near the RFID reader or vice versa. The RFID reader emits electromagnetic signals through its antenna, and small coils embedded on the RFID tag pick up the transmitted signal from the reader. The tag (passive tag) that is nearby the reader is activated by the power of the reader. Once the tag is activated, it sends radio waves back to the reader using the same antenna coils using the inductive coupling (back-scatter coupling) method. The reader picks up the electromagnetic signal of the tag and interprets the frequency and finally translates it into meaningful data using the software. The working mechanism of the RFID technology is shown in the above (Figure I.23).

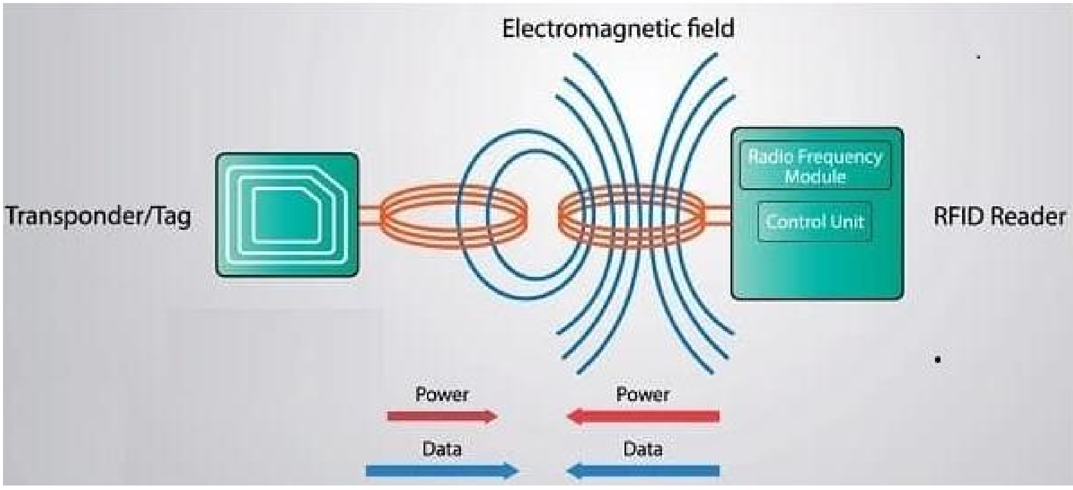

Figure I.23: Working of RFID technology [28].

I.9 Communication of RFID « data transfer »:

As shown in (Figure I.24) airborne data communication between reader and tag is bidirectional. With data transfer taking place in both directions from reader to tag **-downlink-**, and from tag to reader **-uplink-**.In most cases, communication is initiated by "the Reader" [30].

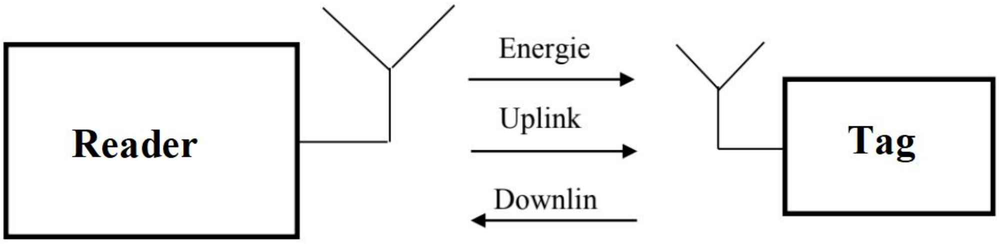

Figure I.24: Schematic representation of RFID communication [29].

There are two types of communication protocol between tag and reader: **TTF** (Tag Talk First) and **RTF** (Reader Talk First).

In the RTF protocol, data transfer is based on the communication procedure called half-duplex (HDX). In this procedure, downlink data transfer alternates with uplink data transfer.

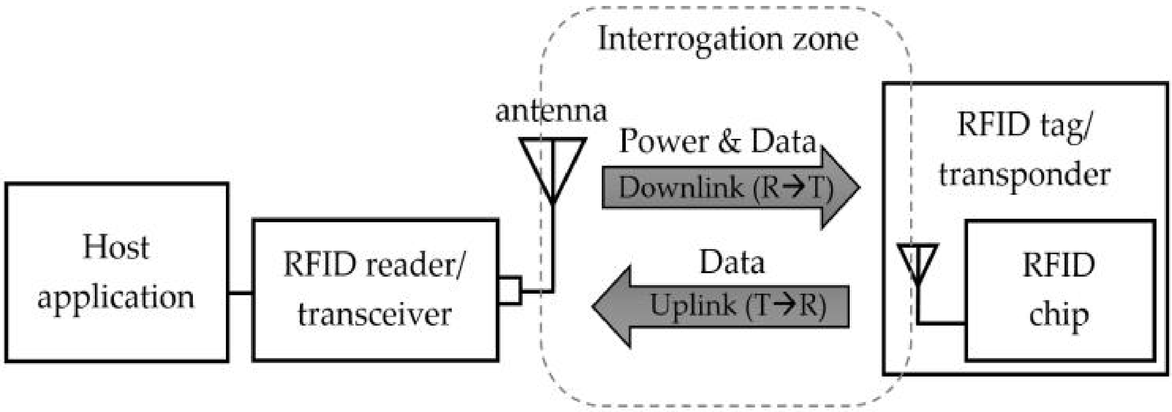

Figure I.25: Link of RFID [30].

I.9.1-Reader-Label Interaction:

The RFID tag can communicate with an RFID reader/antenna, these components must couple together in some way. Coupling is a transfer of energy between two electronic items or two circuits. Two main types of coupling are present in RFID systems: capacitive and inductive. The way that the two circuits couple can determine the read range and frequency of the system. Defined below are coupling techniques along with some frequently used terms in the industry relating to communication.

I.8.1.a -RFID coupling:

Coupling refers to the method of linking or “coupling” the RFID tag and reader/antenna to one another. Coupling allows the reader to recognize and retrieve information from the tag. Inductive and radiative coupling are the two primary types of coupling in an RFID system. Whether inductive or radiative coupling is used typically depends on the frequency level of the tag.

-Inductive Coupling:

An inductively coupled tag consist of an electronic data carrying device, usually a single microchip and a large area coil that functions as an antenna. These always operate passively. This means that it gets its power from reader side. For this purpose, the reader's antenna coil generates a strong electro-magnetic field, which penetrates the cross-section of the coil area and the area around the coil. A small part of the emitted field penetrates the antenna coil of the transponder. By induction, a voltage is generated in the transponder's antenna coil. This voltage is rectified and acts as the power supply for microchip. Inductively coupled systems are based upon a transformer-type coupling between the primary coil in the reader and the secondary coil in the transponder. This is true when the distance between the coils does not exceed so that the transponder is located in the near field of the transmitter antenna [32].

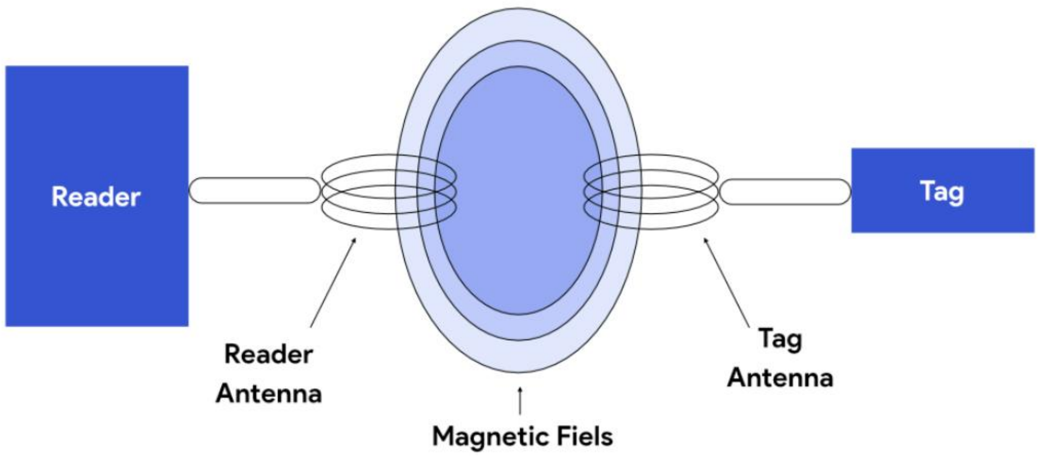

Figure I.25: Schematic diagram of near-field magnetic coupling [31].

-Radiative Coupling:

Radiative coupling is generally leveraged for ultra-high frequency tag coupling. It is sometimes recognized as back-scatter coupling.

The radiative coupling process begins when the reader starts radiating electromagnetic waves. It sends these waves to any nearby tag to capture and reflect back to the reader (back-scatter). We can compare this process to standing in a large field, yelling, and waiting to hear an echo.

Radiative coupling can allow for longer read distances since the tag and reader don't need to be close enough to transfer electricity. However, if the reader is too far away to transmit electricity to the tag, it will require an onboard battery.

As with any process, there are exceptions to the rules. Some near-field UHF tags operate by using inductive coupling as opposed to radiative.

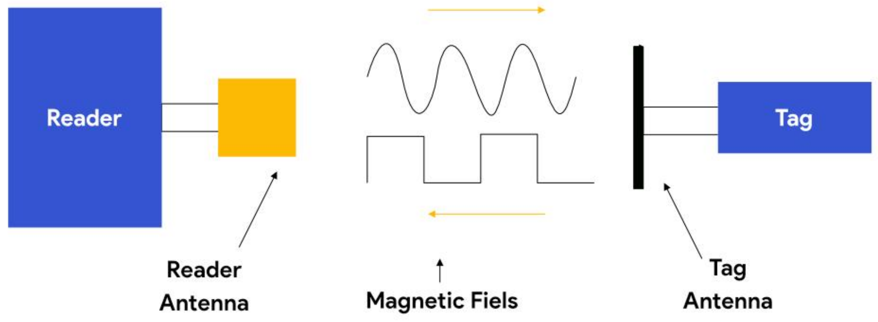

Figure I.27: Far field coupling [31].

I.10 -Advantages of RFID:

RFID Technology provides reliable track and trace services in any environment. It can easily track and provide accurate and real-time information about inventory and product location. The followings are the main advantages/benefits of RFID technology.

- **Cost-effective solution:**

First, RFID tags are relatively cheap to produce, so widespread implementation is less expensive. Second, RFID eliminates the need for manual scanning, reducing labor costs and increasing efficiency. Finally, RFID tags can be read remotely without direct line of sight, allowing for faster and more convenient inventory management. Overall, RFID provides cost-effective solutions for a variety of applications, such as supply chain management, asset tracking, and access control.

- **Saving time through automation:**

With RFID, the process of scanning and identifying items is automated, eliminating the need for manual data entry or barcode scanning. This automation leads to faster and more efficient inventory management, asset tracking, and supply chain operations. RFID tags can be read quickly and accurately, even in bulk or from a distance, saving valuable time and reducing human error. Overall, the automation provided by RFID technology streamlines processes, increases productivity, and allows businesses to allocate their time and resources more effectively.

- **Tracking assets and managing inventory:**

RFID tags make it easy to track and locate items in real-time, helping to reduce time spent searching for misplaced items. This automation saves time and improves the accuracy of inventory management. Additionally, RFID can provide valuable data on inventory levels, allowing companies to optimize their inventory and avoid stockouts or overstocking. Overall, RFID tracking and inventory management streamline operations, help save costs ,and increase efficiency.

- **Improved data accuracy and availability:**

These are significant advantages. Unlike manual data entry or barcode scanning, RFID tags can be read simultaneously and wirelessly, reducing human error and increasing data accuracy. The real-time nature of RFID tracking ensures that data is always up-to-date, providing accurate and timely information for company decision-making. Increased data accuracy and availability enable better inventory management, supply chain visibility, and overall operational efficiency. With RFID, companies can make smarter decisions based on reliable and readily available data.

- **Better control of production:**

RFID tags, businesses can track the movement of raw materials, work-in-progress items, and finished products throughout the production line. This real-time visibility allows for better coordination, improved quality control, and reduced errors or bottlenecks. RFID technology enables businesses to have a clearer understanding of their production flow, identify inefficiencies, and make adjustments to optimize the production process. This ultimately leads to increased productivity, cost savings, and better overall control of the production operations.

- **Shorter process:**

RFID tags can be used to automate tasks such as inventory management, asset tracking, and supply chain operations, reducing the time and effort spent on manual tasks. For example, in inventory management, RFID technology can scan items faster and more accurately, eliminating the need to manually scan barcodes. This automation can reduce processing time, increase efficiency, and increase overall productivity. RFID technology helps companies' save time and resources by simplifying and speeding up processes.

- **Enhanced quality and traceability:**

RFID tags can provide valuable information about the quality and origin of products. With RFID, businesses can track and trace items throughout the supply chain, from production to delivery. This allows for better quality control by identifying any issues or defects that may arise during the manufacturing process. Additionally, RFID tags can store data such as production dates, batch numbers, and expiration dates, providing enhanced traceability. This helps businesses ensure product authenticity, comply with regulations, and quickly identify and address any issues related to product quality or safety. Overall, RFID technology enhances the quality and traceability of products, contributing to customer satisfaction and regulatory compliance.

- **Enhancing health and safety:**

RFID technology can also improve health and safety across industries. For example, in healthcare, RFID tags can be used to track medical equipment and ensure it is properly sterilized and maintained. This helps prevent the spread of infection and ensures patient safety. In construction or hazardous environments, RFID tags can be attached to workers' helmets or safety equipment to monitor their location and ensure they are in a safe area. RFID can also be used to track and manage hazardous materials and improve safety protocols. Overall, RFID technology provides real-time visibility and monitoring, promoting a safer work environment and reducing risk.

➢ **Increased revenues:**

The key advantage of RFID for increasing revenues lies in its ability to enhance operational efficiency. Through the implementation of RFID technology, companies can automate and optimize processes such as inventory management, logistics, and product traceability. This leads to a reduction in errors, faster workflow, and enhanced data accuracy. Consequently, companies are better equipped to meet customer demand, prevent stockouts, optimize inventory levels, and enhance the overall customer experience. These improvements directly contribute to increased sales by boosting efficiency and customer satisfaction.

➢ **Rapid payback time:**

This means that the economic benefits of using RFID, such as reducing labor costs and saving time, can offset the initial cost of implementing the RFID system within a relatively short period of time. For example, by automating inventory management with RFID tags, businesses can save time and money by reducing counting errors, improving process efficiency, and avoiding stockouts.

I.11 -Limitations of RFID:

Besides the numerous advantages of RFID technology, there are some limitations/disadvantages. Some of them are as follows:

➢ **The cost of implementation is higher as compared to barcode scanners:**

RFID systems require specialized equipment, such as RFID readers and tags, which can be more expensive than traditional barcode scanners. However, it's important to consider the long-term benefits and cost savings that RFID can provide, such as improved efficiency, reduced labor costs, and better inventory accuracy. While the upfront cost may be higher, RFID technology offers advantages that can outweigh the initial investment in the long run.

➢ **Implementation can be complex and time-consuming:**

Setting up an RFID system requires careful planning, including tag placement, reader positioning, and system integration. Additionally, configuring and fine-tuning the system can take time and expertise. However, once the system is properly implemented, the benefits of RFID technology, such as improved inventory accuracy and real-time tracking, can outweigh the initial complexity and time investment. It's important to consider these factors when deciding to implement RFID in a business setting.

- **Signals from RFID readers can be blocked by any metal surface and thick materials:**

This can affect the readability and accuracy of RFID tags, especially if they are located behind or within such materials. It's important to consider the environment and potential obstacles when designing an RFID system to ensure optimal performance. However, advancements in RFID technology have led to the development of specialized tags and readers that can mitigate this limitation to some extent.

- **Accuracy is affected by signal quality (any obstruction could cause an error in data):**

Any obstructions or interference in the signal path can lead to errors in data transmission or reading. This can happen if there are physical barriers, electromagnetic interference, or even if the tags are not properly aligned or positioned. It's important to ensure a clear and reliable signal path for accurate data capture and transmission. However, with proper system design and optimization, these accuracy issues can be minimized to a great extent.

- **Privacy and security problems with increased use of tags (especially personal information):**

Especially when personal information is involved. Since RFID tags can store and transmit data, there is a risk of unauthorized access or data breaches. If personal information is stored on the tags, there is a possibility that it could be intercepted or misused. To address this limitation, it's important to implement security measures such as encryption and access controls to protect the privacy and integrity of the data.

Conclusion:

In conclusion, RFID technologies have become indispensable for businesses and individuals. They offer enhanced convenience, efficiency, and security in various everyday applications.

At the beginning of this chapter, we discussed the history and applications of RFID technology. In the next, RFID Components, frequency of operation and RFID System Standards were presented. Finally, Communication of RFID, advantages and limitations were described.

The chapter aims to give the reader an overall view of RFID technology, with emphasis on RFID tags and readers, which are the essential components of RFID.

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Chapter II

State of the art RFID Antennas

II.1 Introduction:

Antennas are now one of the key components of wireless systems modern. The purpose of an antenna is to convert the electrical energy of a signal into radiated electromagnetic energy carried by electromagnetic waves (Vice-versa). The transmission of energy through electromagnetic waves therefore allows the transmission of information over a channel or radio link without physical support, provided that the electromagnetic waves are modulated by an information signal, therefore, the antenna is always the first or last element in the transmission chain .There are several technologies for manufacturing antennas, each with its own characteristics and used in specific applications.

In this second chapter, we'll explore the different types of RFID antennas and the miniaturization techniques used in this exciting technology. We'll also look at the concept of metamaterials, which play a crucial role in the design of compact RFID antennas.

II.2 Antenna basic parameters:

Antennas have several fundamental parameters that determine their operation and performance. To characterize a tag antenna, there are two main parameters to consider: "Radiation parameters" , which refer to the characteristics of electromagnetic radiation emitted by a source, and "electrical parameters", which refer to the electrical characteristics of an equivalent circuit of the antenna.

II.2.1 Radiation parameters:

II.2.1.a - Radiation Pattern:

An antenna pattern is a measure of the radiation in a sphere all around the antenna. Typically, antenna radiation patterns are given as E-plane or H-plane cuts of the sphere. The E-plane pattern contains the maximum electric field vector and the H-plane contains the maximum magnetic field vector.

An antenna radiation pattern or antenna pattern is defined as “a mathematical function or a graphical representation of the radiation properties of the antenna as a function of space coordinates". In most cases, the radiation pattern is determined in the far-field region and is represented as a function of the directional coordinates. A radiation pattern can be defined in two ways:

- ✧ **Power radiation pattern** is the spatial representation of the normalized power pattern which has a maximum value of **1**, it is denoted **r(θ, ϕ)** and obviously depends on both angles in the spherical coordinates system. It is defined as:

$$r(\theta, \varphi) = \frac{P(\theta,\phi)}{P_0(\theta_0,\phi_0)} \tag{II.1}$$

- ✧ **Field Radiation Pattern** is the spatial representation of electric field intensity. The normalized feature, denoted as **f (θ,ϕ),** is defined as:

$$f(\theta, \phi) = \frac{|E(r,\theta,\phi)|}{|E_0(r,\theta_0,\phi_0)|} \tag{II.2}$$

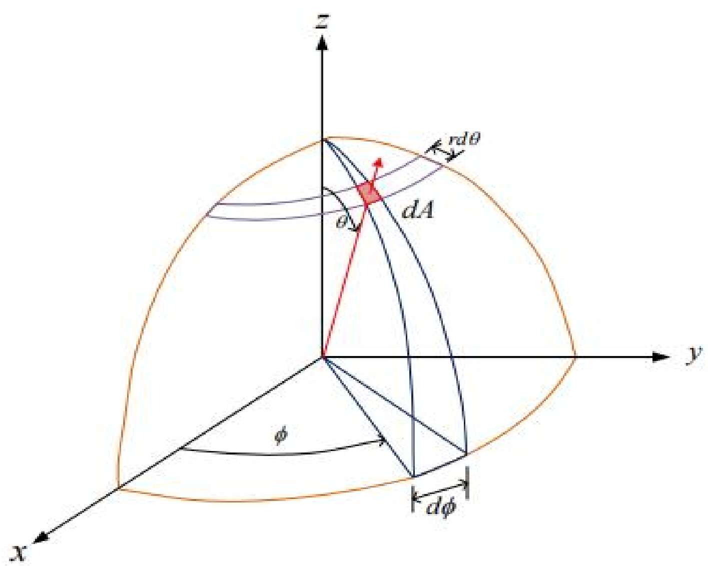


Figure II.1: Spherical coordinates and differential area element [1].

Many parameters of antenna radiation are defined by the radiation pattern, such as beamwidth, power level, and side lobe directivity, providing information about the antenna's ability to radiate into space, When energy is transmitted, the radiation diagram typically shows a main lobe where the maximum gain is concentrated. However, some of that energy is lost in unwanted directions, causing side lobes to appear.

A crucial feature of the radiation pattern is the Half-Power Beam Width **(HPBW)** at -3dB: it plays an important role in defining the two directions of the main lobe where the radiated power is half the maximum power (-3 dB). This angle also characterizes the directivity of the antenna, indicating the most favorable direction.

In Figure II.2, All three patterns yield the same angular separation between the two half-power points, 38.64◦, on their respective patterns, referred to as HPBW.

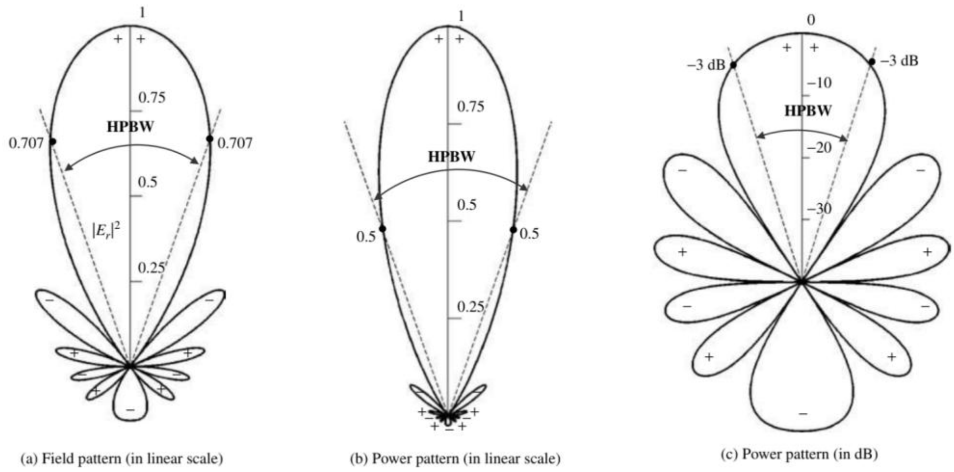


Figure II.2: Three patterns with identical beamwidth angle [2].

Another important parameter is the First-Null Beamwidth **(FNBW)**, which is the angular spread between the first two nulls in the pattern (Figure II.3).

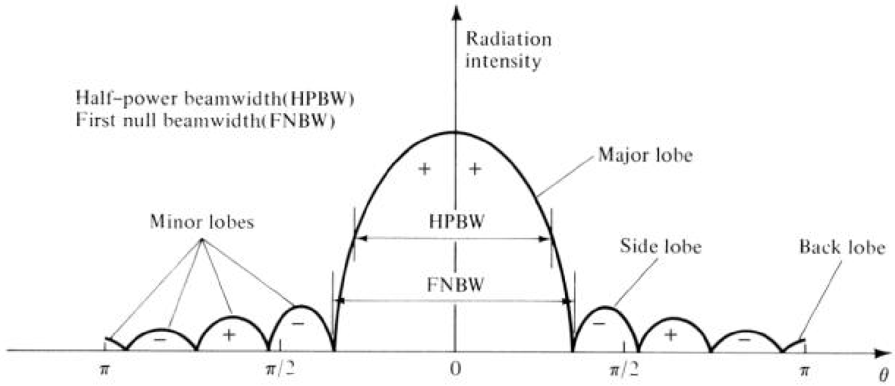


Figure II.3: 2D power pattern for an arbitrary antenna and its associated lobes and parameters[2].

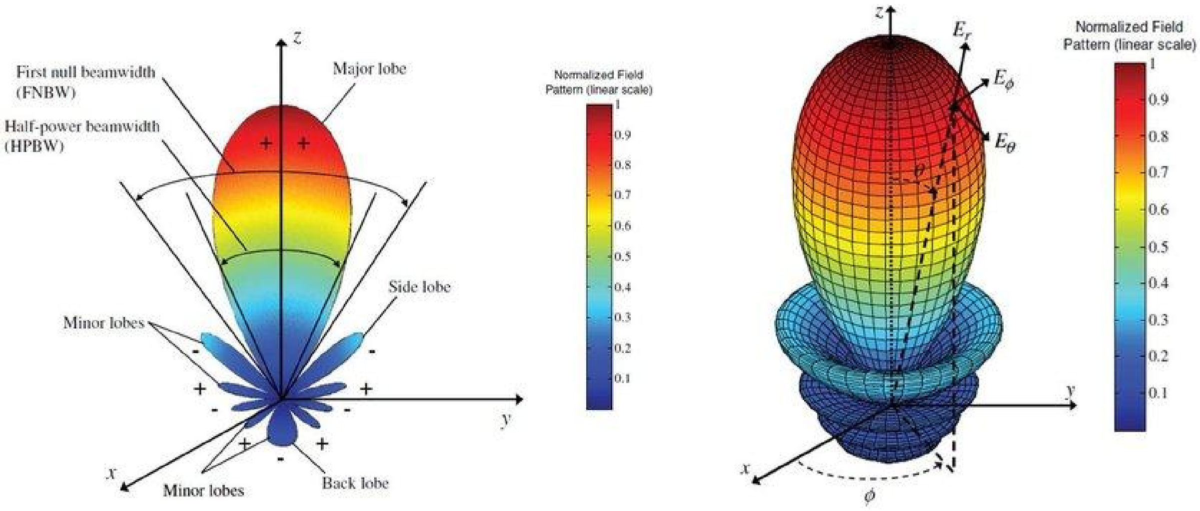


Figure II.4: 3D power radiation pattern of antenna [3].

-Radiation Pattern Lobes :

A radiation lobe is a portion of the radiation pattern bounded by regions of relatively weak radiation intensity. The pattern consists of main lobe, minor lobes, side lobes and back lobes (Figure II.5).

Minor lobes usually represent radiation in undesired directions, and they should be minimized. Side lobes are normally the largest of the minor lobes.

The level of minor lobes is usually expressed as a ratio of the power density, often termed the side lobe ratio or side lobe level.Additionally, antennas may exhibit a back lobe, which refers to radiation in the direction opposite to the main lobe. Minimizing back lobes is also crucial as they contribute to interference and reduce the effectiveness of signal transmission.

In most radar systems, low side lobe ratios are very important to minimize false target indications through the side lobes (e.g., -30 dB).

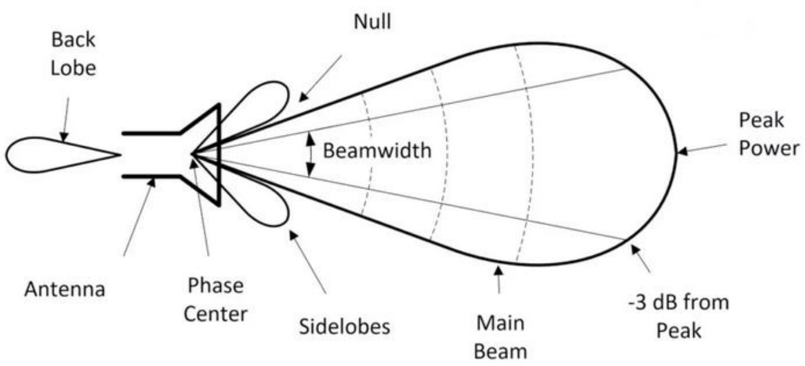


Figure II.5: Radiation Pattern Lobes [4].

-Typical Radiation Pattern Shapes:

Radiation patterns are used to identify the areas of surrounding space antenna and the direction of strong or weak radiation. Although each radiation pattern may vary from antenna to antenna, there are three typical radiation pattern shapes (Figure II.6):

Isotropic antenna: This type of antenna radiates its energy evenly in all directions of space. However, it remains purely theoretical and serves as a reference to establish the directivity or gain of an actual antenna.

Directional antenna: An antenna is considered directional when it radiates more power in one direction than in others.

Omnidirectional antenna: It is designed to be non-directional, meaning it can transmit or receive signals from any direction without the need for pointing or adjusting its orientation, omnidirectional antennas receive signals equally from all directions, unlike directional antennas that pull in signals better from one specific direction.

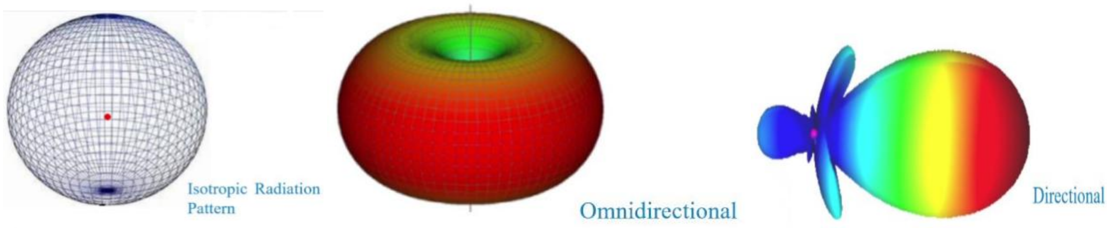


Figure II.6: Three dimensional radiation patterns [5].

II.2.1.b-Field regions:

The space surrounding the antenna is divided into three regions, based on the behavior of the fields, which are reactive near-field, radiating near-field (or Fresnel), and far-field (or Fraunhofer) as shown in Figure II.7. For an antenna whose largest dimension is **D**, the reactive near-field region is the region immediately surrounding the antenna where the fields predominately do not radiate. For an electrically small antenna, the radius of this sphere is denoted by:

$$R_1 = \lambda/2\pi \quad (II.3)$$

For larger antennas, this region is denoted:

$$R_1 = 0.62\sqrt{\frac{D^3}{\lambda}} \quad (II.4)$$

The tags at LF and HF frequencies are mostly loop or inductive coil antennas and operate in this region.

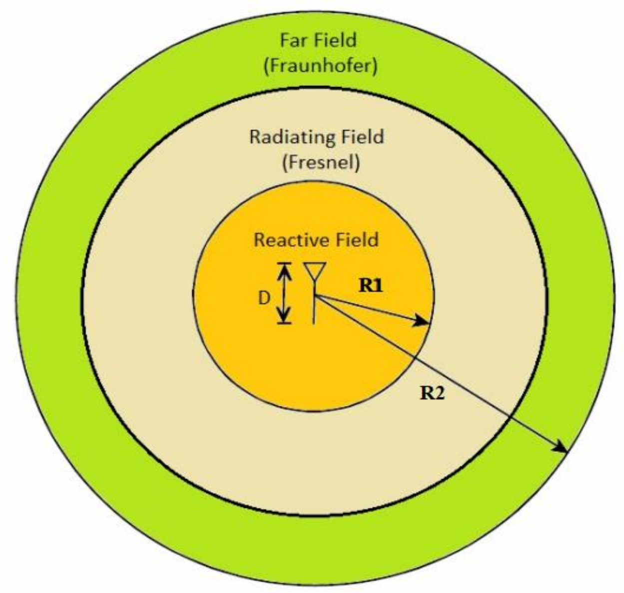


Figure II.7: Field regions of an antenna [6].

The radiating near field, or Fresnel region, lies between the reactive near-field region and the far-field region. In this region, the fields are predominately radiating, and the angular field distribution depends on the distance from the antenna. If the antenna is small, this region may not exist. For larger antennas, the inner radius of this spherical region is given by (Figure II.7):

$$R_2 = \frac{2D^2}{\lambda} \quad \text{(II.5)}$$

The far-field or Fraunhofer region: is the region where the fields are radiating and their angular variation is essentially independent of the distance from the antenna, and the field components predominantly lie in the transverse plane relative to the direction of propagation. In this region, traveling waves dominate and are characterized by a decay rate of $1/R_2$, where R_2 is the distance from the antenna to the observation point in the far-field region. These traveling waves serve to carry electromagnetic power to passive and semi-passive UHF and microwave transponders (Figure II.7).

II.2.1.c -Directivity:

The directivity **D (θ, ϕ)** of an antenna is a parameter that expresses the ratio of the intensity of the radiation in a given direction relative to the average intensity in the all directions. For an isotropic antenna, the directivity is the unit. When describing of an antenna, its directivity often refers to the maximum directivity, in the direction at which the antenna emits the maximum radiation intensity. It can be summed up by the formula following:

$$D(\theta, \phi) = \frac{P(\theta,\phi)}{P_{rad}/_{4\pi}} = \frac{4\pi * P(\theta,\phi)}{P_{rad}} \qquad (II.6)$$

Where :

$D(\theta, \phi)$= Directivity (dimensionless)

$P(\theta, \phi)$ = Radiation intensity (W/sr)

P_{rad}= total radiated power (W)

ϕ: $[0\ , 2\pi]$, **θ**: $[0, \pi]$

$P_{rad} = \iint P(r, \theta, \phi)\, ds$,$ds = r^2 \sin\theta d\theta d\phi$

- **Maximum directivity :**

$$D_0 = \frac{4\pi * P_0}{\int_0^{2\pi}\int_0^{\pi} P(\theta,\phi)\sin\theta * d\theta * d\varphi} \qquad (II.7)$$

P_0 = Maximum power.

II.2.1.d -Gain:

Gain is the most crucial performance parameter of an antenna. It is closely related to the antenna's directivity. But the difference between them is that the gain takes into account the efficiency and directivity of antenna together. Hence the gain given by:

$$G(\theta, \phi) = \eta_{ray} \times D(\theta, \phi) \qquad (II.8)$$

It can also be defined as the ratio of the radiation intensity in a given direction from the antenna to the total input power delivered to the antenna port divided by 4π.

It is expressed as [7]:

$$G(\theta, \varphi) = 4\pi \frac{p(\theta,\phi)}{P_{in}} \qquad (II.9)$$

As for directivity, gain is a dimensionless quantity so it is generally expressed in decibels dB:

$$G_{dB} = 10 \log_{10}(G) \qquad (II.10)$$

G is the maximum value of the gain:

– It can be lower than 1 (0 dBi).

– In dBi: 10 log G.

II.2.1.e- Antenna Efficiency:

The overall antenna efficiency is computed by taking into account all losses of the antenna. Simply put, it is the ratio of energy radiated over the energy supplied at the input port:

$$\eta_{rad} = \frac{P_{rad}}{P_{in}} \quad \text{(II.11)}$$

The maximum value of the gain is related to the maximum directivity**:**

$$\eta_{rad} = \frac{G}{D_0} \quad \text{(II.12)}$$

The difference between the $\boldsymbol{P_{in}}$ power available at the input and the $\boldsymbol{P_{rad}}$ at the output corresponds to the various losses (joules and dielectric) in the antenna, which can be characterized by the radiation efficiency.

II.2.1.f -Field polarization:

Polarization is defined as the curve traced by the end point of the arrow (vector) representing the instantaneous electric field. The field must be observed along the direction of propagation. There are two types of polarization, circular and linear polarization.

Linear polarization: The polarization of an antenna is determined by the direction of the electric field. In linear polarization, the electric field vector changes only in magnitude. Polarization mismatch occurs when the polarization of the receiving antenna is not equal to the polarization of the incoming wave [9].

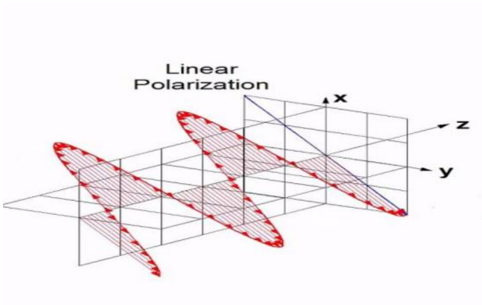


Figure II.8: linear polarization [8].

Circular polarization: In circular polarization, the electric field at that point traces a circle as a function of time and it only can be achieved when the magnitude of two components are same . Axial ratio can used to determine the quality of the circular polarization. Circularly polarized antennas can be achieved using various techniques such as slots, truncated corners, nearly square patches, double layers, and others [10].

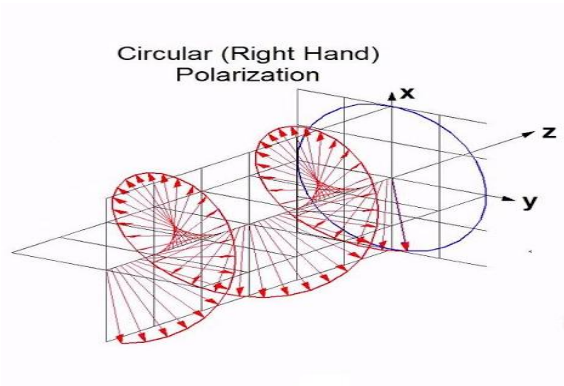


Figure II.9: Circular polarization [8].

Elliptical polarization: is a characteristic of electromagnetic waves in which the electric field oscillates along an elliptical trajectory. Unlike linear polarization, where the electric field oscillates in a fixed direction, and circular polarization, where the electric field describes a circular trajectory, elliptical polarization is a combination of both.

Elliptical polarization can be achieved by superimposing linear and circular polarization with appropriate amplitudes and phases. Electromagnetic waves with elliptical polarization have applications in wireless communications, remote sensing, radar imaging, and other fields where additional flexibility in the orientation of the electric field is needed to optimize system performance [11].

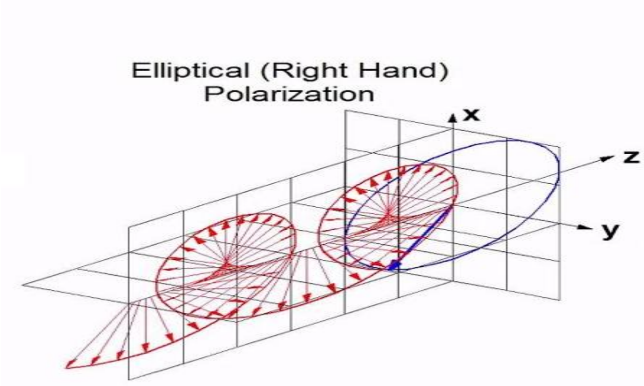


Figure II.10: Elliptical polarization [8].

II.2.2 Electrical parameters:

II.2.2.a -Impedance:

Impedance is defined as the resistance to the flow of electricity in a component circuit and is measured as the ratio of voltage (V) to current (I):

$$Z = \frac{V}{I} \tag{II.13}$$

From an electrical perspective, an antenna is characterized by its impedance. The expression for impedance is the complex form $\boldsymbol{Z_a}$, where the real part is a radiation resistance $\boldsymbol{R_a}$ and imaginary part reactance and loss $\boldsymbol{X_a}$, It is defined as:

$$Z_a = R_a + jX_a \tag{II.14}$$

Where: $\mathbf{Z_a}$,$\mathbf{R_a}$ and $\mathbf{X_a}$ are the impedance, resistance, and reactance, respectively, of the antenna, at its input terminals.

The energy dissipated by $\mathbf{R_r}$ corresponds to the energy radiated by the antenna, and the energy dissipated by $\mathbf{R_l}$ corresponds to conduction losses, dielectric losses, and surface wave losses of the antenna:

$$R_a = R_r + R_l \tag{II.15}$$

II.2.2.b -The Reflection Coefficient:

Antenna return loss is a measure of the amount of energy returned back to the input port and is an important antenna performance term.

Generally, the antenna is designed to be matched to the characteristic impedance $\boldsymbol{Z_0}$ of a transmission line (typically 50 Ω or 75 Ω), The reflection coefficient of an antenna is then defined as:

$$\Gamma = S_{11} = \frac{Z_a - Z_0}{Z_a + Z_0} \tag{II.16}$$

The reflection coefficient $\boldsymbol{S_{11}}$ is always less than or equal to 1, and is defined in decibels (dB) by:

$$S_{11} = 20 \, log\Gamma \tag{II.17}$$

- The antenna matching condition : $\mathbf{Z_0 = Z_a \Rightarrow \Gamma = 0}$

II.2.2.c -VSWR:

VSWR (Voltage Standing Wave Ratio) is a measure of how efficiently radio-frequency power is transmitted from a power source, through a transmission line, into a load (for example, from a power amplifier through a transmission line to an antenna). The 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 (Figure II.9). 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. VSWR is the voltage ratio of the signal on the transmission line.

$$\text{VSWR} = \frac{|V_{(max)}|}{|V_{(min)}|} \tag{II.18}$$

Where:

$\mathbf{V_{(max)}}$ is the maximum voltage of the signal along the line, and $\mathbf{V_{(min)}}$ is the minimum voltage along the line.

It can also be derived from the reflection coefficient:

$$\text{VSWR} = \frac{1+|\Gamma|}{1-|\Gamma|} \quad \text{(II.19)}$$

If the load and transmission line are matched, **Γ = 0**, and **VSWR = 1.0**

The reflection coefficient can be calculated if we already know the VSWR :

$$|\Gamma| = \frac{\text{VSWR}-1}{\text{VSWR}+1} \quad \text{(II.20)}$$

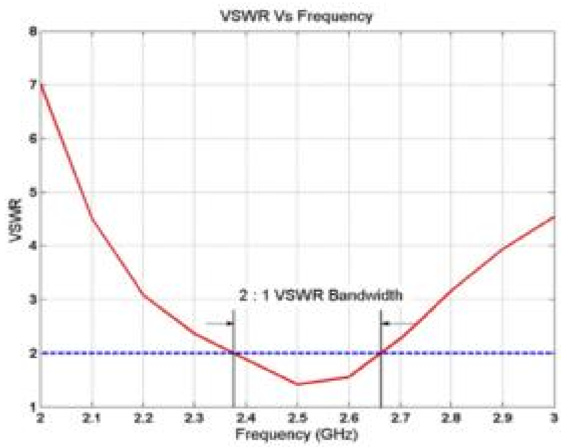


Figure II.11: Example of VSWR vs frequency [12].

II.2.2.d -The Bandwidth :

Bandwidth is another fundamental antenna parameter. Bandwidth describes the range of frequencies over which the antenna can properly radiate or receive energy. Often, the desired bandwidth is one of the determining parameters used to decide upon an antenna, as shown in the following expression:

$$\text{BW} = F_H - F_L \quad \text{(II.21)}$$

For narrow-band antennas, the bandwidth is expressed as a percentage of the frequency difference $(\mathbf{F_H - F_L})$) over the center frequency (F_C) of the bandwidth [21],[22]:

$$B = 100 \times \frac{F_H - F_L}{F_C} \; [\%] \quad \text{(II.22)}$$

BW : Bandwidth.

B : Relative bandwidth.

F_H = Highest frequency.

F_L = Lowest frequency.

F_C = the center frequency in the band.

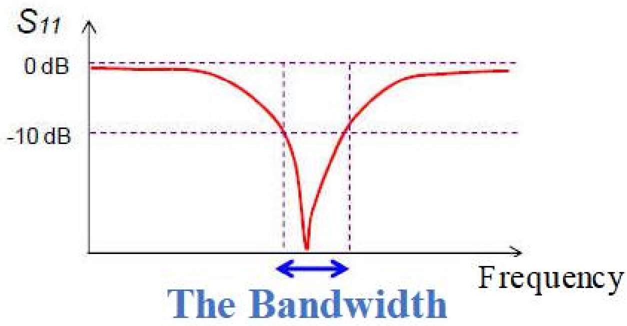


Figure II.12: Example of a bandwidth [13].

II.2.2.e -Quality factor:

The Quality Factor (Q) of an antenna is computed from the ratio of the bandwidth to the center frequency. If the antenna operates over a band between $\mathbf{F_L}$ and $\mathbf{F_H}$ with center frequency $F_C = \frac{F_H+F_L}{2}$, then the Q is given by:

$$Q = \frac{F_c}{F_H - F_L} \qquad \text{(II.23)}$$

If the loss of the antenna is known along with the Return Loss, Q can be calculated by the following:

$$Q = \frac{f_r}{Bp} \qquad \text{(II.24)}$$

II.2.2.f -Reading distance:

The read distance, also known as the read range, is one of the most important factors in evaluating the performance of a tag's antenna design. It is given by the formula [14]:

$$d_{max} = \frac{c}{4\pi f}\sqrt{\frac{EIRP_R}{P_{th}} * \tau G_{Tag}(\theta, \varphi)} \qquad \text{(II.25)}$$

$$EIRP = P_t.G_t \qquad \text{(II.26)}$$

$\boldsymbol{G_{Tag}(\theta, \varphi)}$:is the tag antenna gain

$$G(\theta, \phi) = eD(\theta, \phi)(1 - |\Gamma^*|^2) \qquad \text{(II.27)}$$

$EIRP_R$: Equivalent isotropic radiated power

G_t : Gain of the transmitting antenna

P_{th}: Puissance chip sensitivity

According to the formula above, the read distance depends on the following parameters: Frequency **($\mathcal{F}$),** equivalent isotropically radiated power ($EIRP_R$), chip sensitivity (P_{th}), transmission coefficient **(τ)**, and antenna gain ($\mathbf{G(\theta, \phi)}$).The first three parameters are initially set and will remain unchanged during the design process. Since the transmission coefficient**(τ)** depends on the impedance matching between the chip and the antenna, the read distance will be significantly affected if the adaptation between the chip and the antenna is not ensured. On the other hand, the antenna gain depends on the structure chosen during the design and influences the read distance of the system. Additionally, the read distance also depends on the object on which the tag is placed. Indeed, factors such as the dielectric constant, loss tangent, and thickness of the object have a significant influence on the antenna gain, resonance frequency, and impedance matching [15].

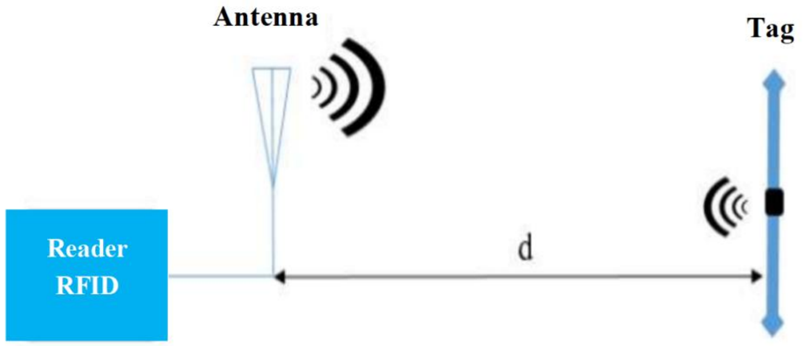
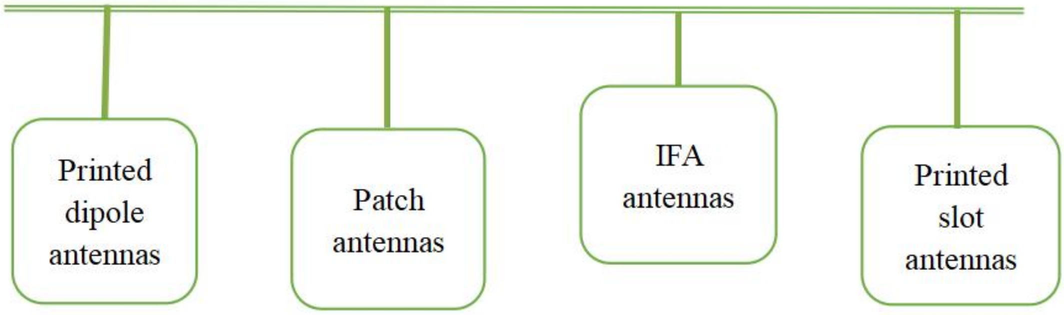


Figure II.13: Illustration of the reading distance between an RFID reader and a tag [16].

II.3 The Main Types of RFID Tag Antennas:

RFID tag antennas play a crucial role in the wireless communication between tags and RFID readers .They transmit and receive radio frequency signals that carry the data [17].

There are several commonly used types of antennas; each type of antenna has its own characteristics and performances, making them suitable for different applications and environments. The four main types of antennas used are:



II.3.1- Dipole antennas:

Dipole antennas consist of two conductive elements, usually metal, powered by a radio frequency signal (Figure II.14). These two enables wireless communication between RFID tags and readers [18].

Dipole antennas have several advantages, they are relatively easy to manufacture and integrate into RFID tags, offering good signal transmission and reception efficiency, which allows for reliable communication between tags and readers. . Additionally, they are omnidirectional, meaning they can receive and transmit signals in all directions, which is ideal for applications where tags can be oriented in different ways. However, the performance of dipole antennas can vary depending on their size, shape, and position relative to the tags and readers. Adjustments may be necessary to optimize antenna performance for specific application [19].

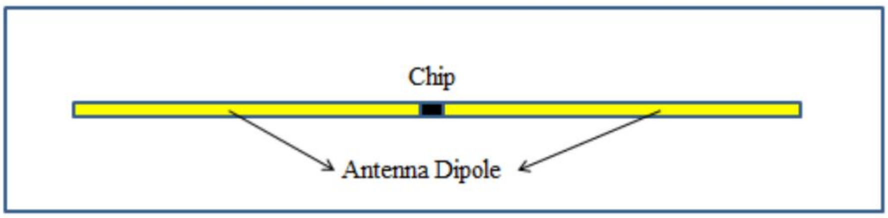


Figure II.14: Classic Antenna dipole [14].

Dipole antennas can be printed in RFID technology (Figure II.15). Printing techniques such as screen printing or conductive inkjet printing (Figure II.16). These techniques allow for the fabrication of dipole antennas directly into flexible substrates, such as RFID tags or smart cards.

This provides flexibility and design possibilities to integrate RFID antennas into different shapes and sizes of products. Printing dipole antennas is widely used in the industry to produce affordable and customized RFID labels.

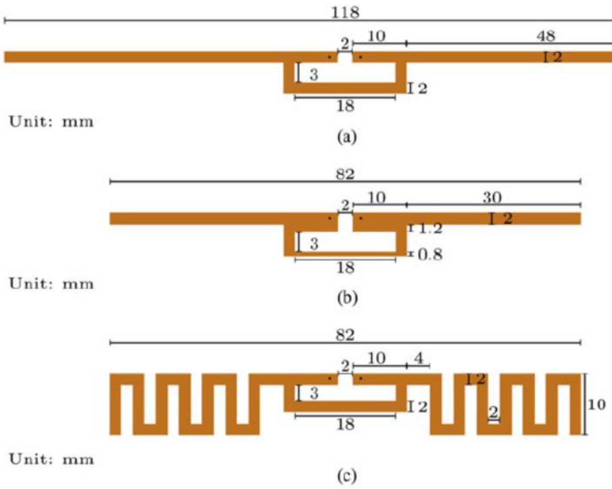


Figure II.15: Illustration of dipole antenna miniaturization with meander line structure [20].

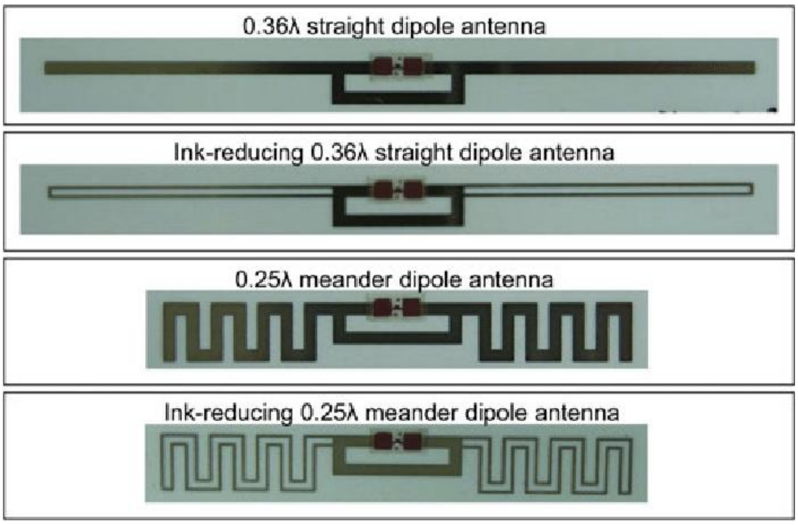


Figure II.16: Fabricated inkjet-printed RFID tag antennas,(a) a straight dipole antenna with a total length of 0.36**λ**, (b) lnk-reducing 0.36**λ** straight dipole antenna, (c) a meander dipole antenna with a total length of 0.25**λ**, and (d) lnk-reducing meander dipole antenna with a total length of 0.25**λ**[20].

II.3.2- Patch antennas:

Patch antennas, also known as planar antennas, are antennas with printed radiating elements. The concept of patch antennas emerged in the 1950s and today they are widely used in many electronic devices [21] .They come in various shapes, such as rectangles, squares, annular ring circular disks or triangles (Figure II.17), and generally consist of a dielectric substrate and a ground plane. These antennas are widely used in various fields, including RFID, due to their efficiency and adaptability to different frequencies and environments. For example, in the RFID context, we find UHF RFID patch antennas suitable for indoor use, outdoor use or in specific applications such as small RFID systems or demonstrations [23].

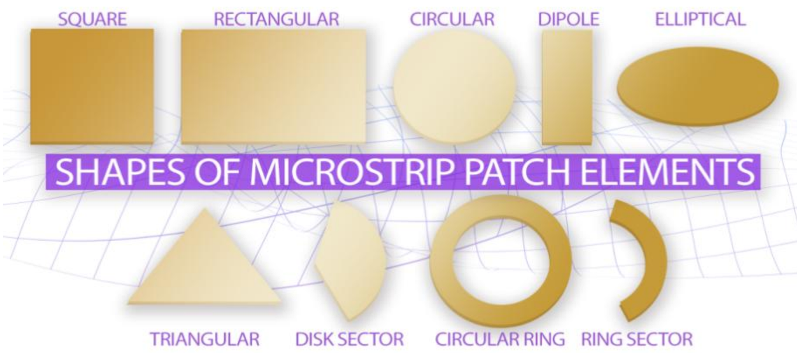


Figure II.17: Different patch shapes [22].

In terms of design, RFID patch antennas can be produced using a variety of manufacturing techniques, including printing on a flexible substrate, metal deposition on a rigid substrate, or even integration of metal wires. They can also be adapted to operate in different environmental conditions, and optimized for specific performances such as read range, directionality, or resistance to interference.

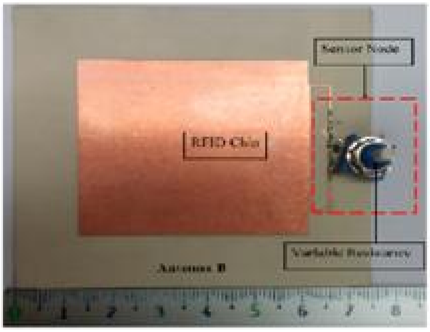


Figure II.18: Examples of Fabricated RFID Patch antennas [24].

II.3.3- Slot antennas:

Slot antennas are devices used for transmitting and receiving electromagnetic waves. The slotted wave-guide antenna consists of one or more rectangular wave-guides with regularly spaced slots. These slots allow the waves to be radiated. The shape and size of the slot, as well as the driving frequency, determine the radiation pattern. Slot antennas are used in a variety of communications applications, notably for frequencies ranging from 300 MHz to 25 GHz, and are common for navigation radars. They are also used in civil and military applications, as well as in other less conventional fields [25].

Slotted planar antennas in RFID systems work by using openings or slots in a metal conductor to transmit and receive radio frequency waves (Figure II.19). When a signal is emitted from the antenna of the RFID reader, it passes through the slots of the slot antenna and creates an electromagnetic field. This electromagnetic field interacts with the RFID tag, which contains an electronic chip and a miniature antenna. When the RFID tag is within range of the slot antenna, it receives the signal and transmits a response containing the information stored in the electronic chip. The slot antenna of the RFID reader then picks up this response and transmits it to the processing system for object identification and tracking. That's how slot antennas enable wireless communication between RFID readers and tags in RFID systems.

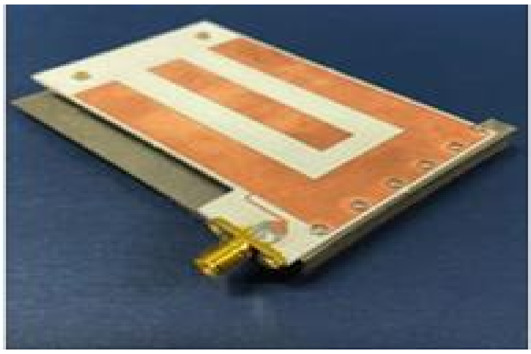


Figure II.19: Fabricated RFID Slot antenna [26].

II.3.4- IFA antennas:

The term "IFA antenna" stands for Inverted-F Antenna, which is known for its compact size, easy construction, and efficiency. IFA antennas are designed to have an impedance of around 50 Ohms, making them suitable for various applications [27]. Compared to other antenna types like MIFA (Monopole Inverted-F Antenna), IFA antennas are preferred for their radiation characteristics and efficiency, especially when space is limited.

These antennas can be further optimized for bandwidth improvement by manipulating conductive parasitic elements, enhancing their performance in terms of return loss and bandwidth. The design of an IFA antenna typically involves a folded monopole with an inductive stub added to enhance its functionality.

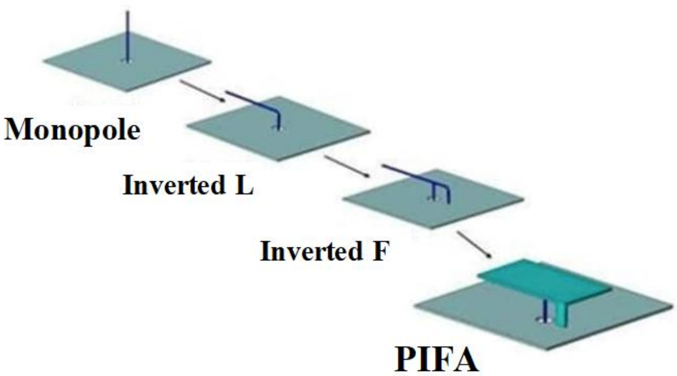


Figure II.20: Different Inverted antenna configurations [28].

IFA antennas, or inverted F antennas, are a specific type of antenna used in RFID technology. They are known for their compact size and versatility. These antennas are designed with a unique shape that resembles an inverted "F".

The Inverted F (Antenna-IFA) consists of a conductor wire placed parallel to the ground plane, a piece of wire for connection to the ground plane, and a feed wire for the antenna (Figure II.21). The length of the vertical wire connected between the conductor wire and the ground plane can be used to adjust the antenna's resistance and capacitance. The main radiating element is the conductor line parallel to the ground plane, while the bonding wire is the cause of power losses. To improve the IFA's bandwidth, the radiation wire will be replaced by a radiation plane, enabling us to obtain a new pattern called PIFA.

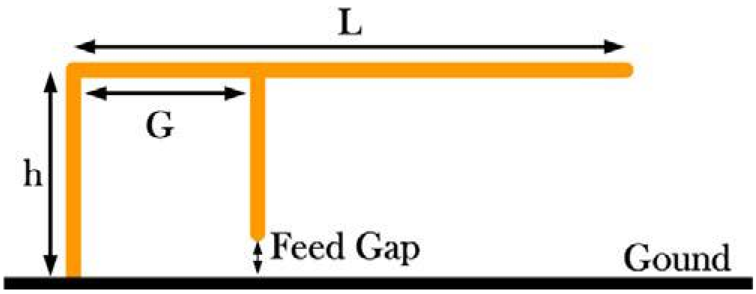


Figure II.21: Geometry of IFA antenna [29].

This design allows for efficient transmission and reception of the radio frequency signals used in RFID communication. IFA antennas offer several advantages. Their small size makes them easy to integrate into various RFID devices and systems. They are also versatile, meaning they can be used in different applications, from wearable devices to stock tracking systems. Additionally, IFA antennas provide good performance in terms of reading range and signal sensitivity.

II.4- Antenna feed:

In the field of antennas, several feeding methods are used to supply an RF signal to the antenna structure [30]. One of these methods, called "Probe Feed" involves using a probe to feed the antenna with RF. In this method, a probe, typically in the form of a small metal wire or a test probe is directly connected to the antenna structure. The probe acts as a direct electrical connection point to the antenna, thereby providing the necessary RF signal for transmission or reception of electromagnetic waves, "Probe Feed" can be modeled in electromagnetic simulations software such as HFSS uses lumped port.

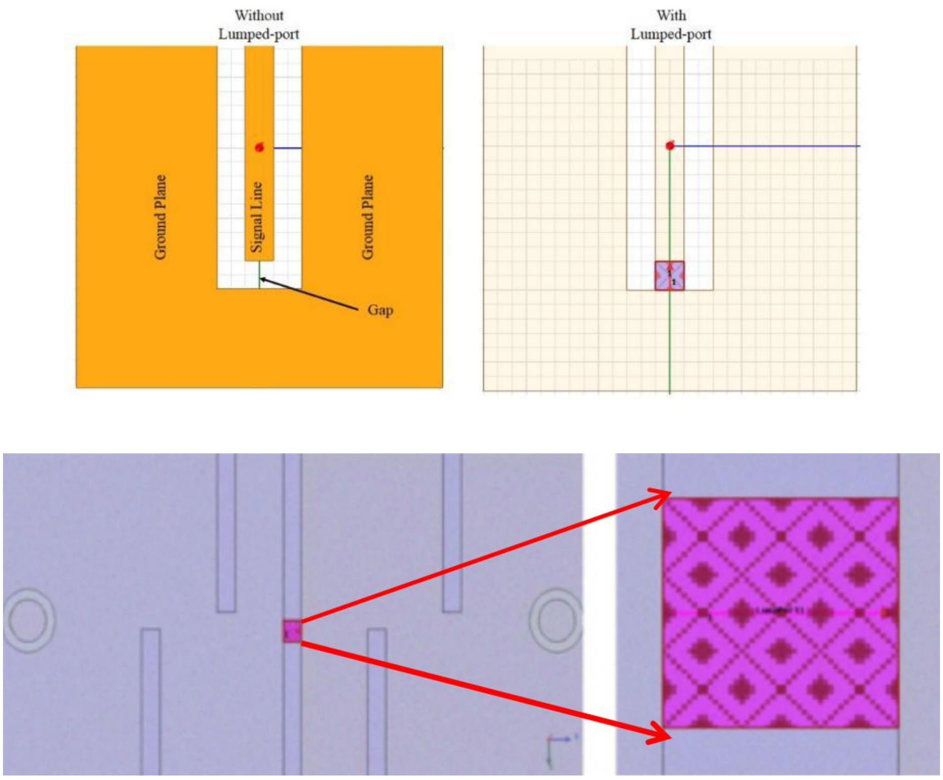


Figure II.22 : Lumped port excitation [31].

"lumped port" is used to represent a point electrical connection to the antenna structure. When simulating a "Probe Feed" in HFSS, a "lumped port" is placed at the location of the probe on the antenna structure. This setup effectively models the connection of the probe to the antenna and provides or extracts the necessary RF signal for simulation. Thus, the "lumped port" serves as a representation of the "Probe Feed" in electromagnetic simulations, enabling the study and analysis of the antenna behavior when fed by this method [32].

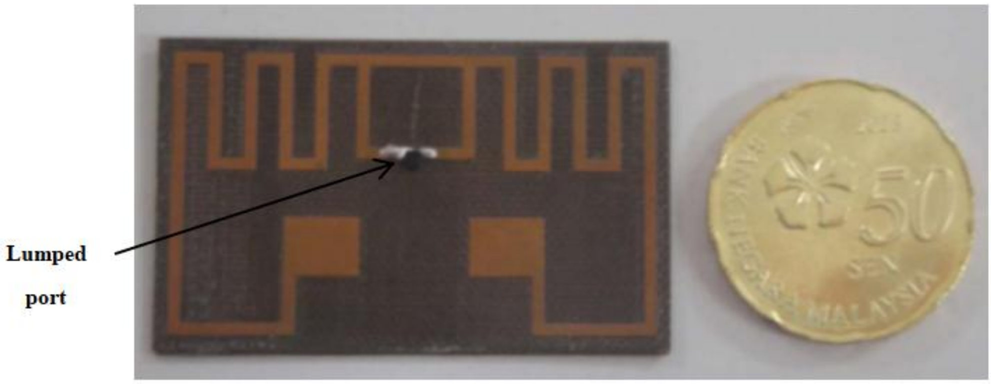


Figure II.23: Example of antenna fabrication using a lumped port [30].

II.5-Miniaturization of Passive RFID Tag Antennas:

Miniaturization of RFID passive antennas is a technique that allows for tags and reduced production costs. Antenna miniaturization refers to the process of reducing the physical size of an antenna while maintaining or improving its functionality and performance. Traditionally, smaller antennas were believed to have limited bandwidth and efficiency. However, advancements in technology have enabled the miniaturization of antennas without compromising their effectiveness [33].

Miniaturizing antennas is essential for various applications, such as in RFID systems, where compact and low-profile antennas are required for easy concealment and portability [35]. While miniaturization has become more achievable, it still requires a combination of mechanical design expertise and electrical engineering proficiency to ensure successful implementation.

Researchers have explored various techniques for antenna miniaturization, including the use of fractal patterns, metamaterial structures; meander lines, capacitive loading, and circularly polarized microstrip patch antennas (CPMPAs). These methods aim to reduce the physical footprint of antennas while maintaining their performance across different frequency bands [34].

II.6- Techniques of miniaturization for each antenna topology:

II.6.1- Folded Dipole antenna:

The most efficient way to miniaturize a dipole antenna is to bend the two dipole arms of the dipole to create a "snake" path. With enough bending, we can make the dipole shorter for the same wire length (Figure II.24).

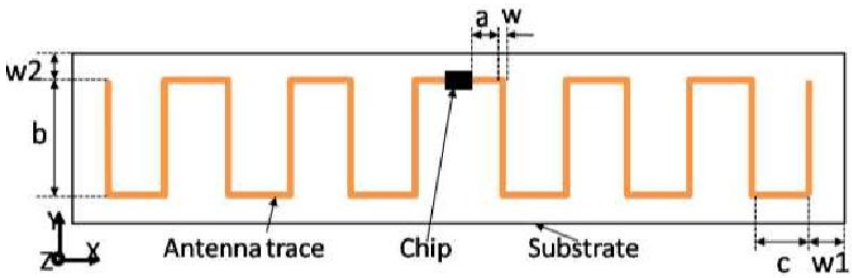


Figure II.24: The geometry of the Folded dipole antenna [36].

II.6.2- Fractal antennas:

Fractal antennas in RFID technology are antennas designed with fractal patterns, which are repetitive and complex mathematical patterns. They offer several advantages. Firstly, they allow for antenna miniaturization while maintaining good performance in terms of range and sensitivity. Secondly, they are more resistant to interference, which improves the reliability of RFID systems. To use them, you simply need to design the antenna using the appropriate fractal patterns and integrate it into the RFID system. It's an exciting technology that contributes to the efficiency and miniaturization of RFID systems [37].

Fractal antennas are designed using geometrical shapes called fractals, which are mathematical constructs characterized by self-similarity and scale invariance. These shapes can be scaled up or down indefinitely while maintaining their essential structure. In the context of antennas, fractals are employed as the radiating elements, which results in antennas that exhibit improved performance across a wide range of frequencies. Also they are using a variety of fractal geometries, such as the Sierpinski triangle, Koch curve, Minkowski fractal, and Hilbert curve, among others (Figure II.25) [38]-[40]. These geometries can be iteratively repeated to create complex structures with unique properties. The choice of fractal geometry depends on the specific requirements of the application, such as frequency range, bandwidth, and directivity.

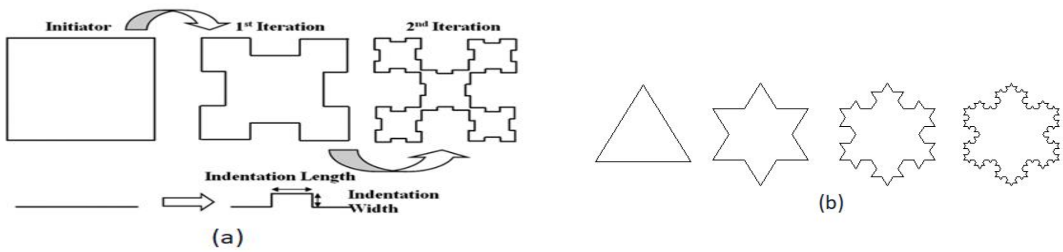


Figure II.25 : Fractals Examples (a) -Minkowski's fractal , (b)-Koch's Star [38].

Fractal antennas can be constructed using various materials and fabrication techniques, including printed circuit boards (PCBs), microstrip lines, and even 3D printing. The choice of material and fabrication method depends on factors such as the desired frequency range, environmental conditions, and manufacturing constraints [39].

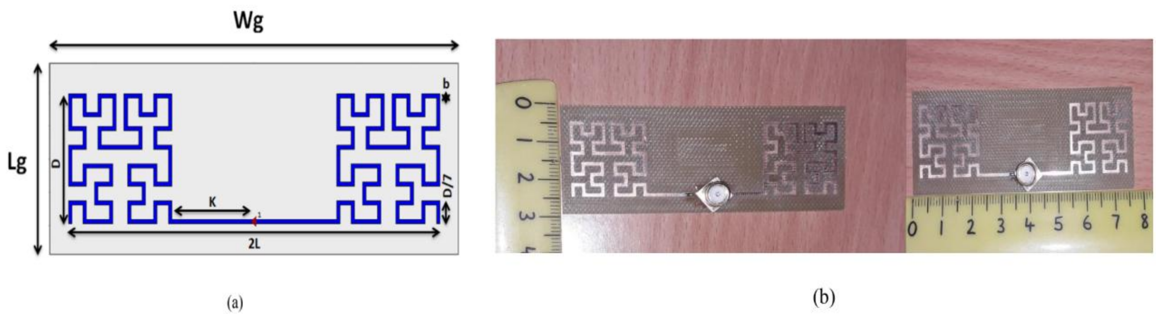
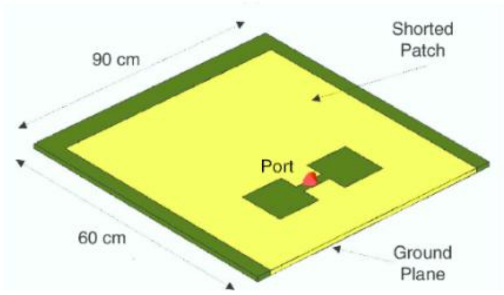


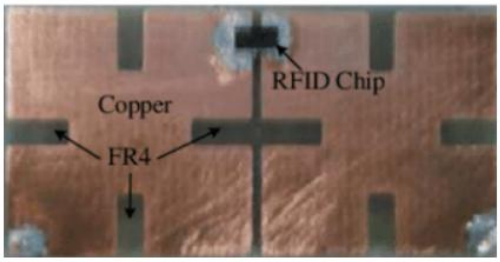
Figure II.26 : Examples (a)-Fractal dipole antenna structure ,(b)-Fractal dipole antenna structure realized [16].

II.6.3- Slotted Patch Antennas:

Slots in RFID patch antennas are openings cut into the antenna's conductive material. These slots act as resonators, reducing the overall length of the antenna while maintaining good radiation performance. By reducing the antenna's length, it can be made more compact and suitable for applications where space is limited. This makes it possible to integrate RFID antennas into small objects, such as labels or cards. The slots are designed to compensate for the reduction in size and maintain high radiation efficiency (Figure II.27).



(a)



(b)

Figure II.27: Slot Patch antennas [25].

II.7- Metamaterial Antennas:

In this study, the method employed to reduce the size of RFID antennas involves the incorporation of metamaterial resonators. Metamaterials are engineered materials with unique electromagnetic properties not found in naturally occurring materials. By integrating metamaterial resonators into the design of RFID antennas, it becomes possible to manipulate and enhance their electromagnetic performance, allowing for the creation of smaller antennas without sacrificing efficiency or range. This approach leverages the unique properties of metamaterials to achieve compact antenna designs suitable for various RFID applications [41].

II.7.1- Overview of metamaterial:

Metamaterials are artificially designed materials with properties different from the naturally occurring materials. Electric permittivity "**ε**" and magnetic permeability "**μ**" are the two basic parameters which describe the electromagnetic property of a material or medium. Permittivity describes how a material is affected when it is placed in electric field. And permeability describes how a material is affected in presence of magnetic field.

Metamaterials may have either negative permittivity or permeability, or both may be negative simultaneously. It is an arrangement of periodic structures of unit cells in which the average size of a unit cell should be much smaller than the impulsive wavelength of the light i.e. $a \ll \lambda$ (Figure II.28)[42]. It was first introduced by Victor Veselago in 1967 after the Second World War [43]. He showed that wave propagation in metamaterial is in opposite direction than the naturally occurring materials. John Pendry discovered a realistic way to design a material in which right handed rule is not applied [44]. In this material, group velocity is antiparallel in direction to its phase velocity. Materials with negative permittivity such as ferroelectrics were available in nature but materials with negative permeability did not exist in nature. Pendry showed that the negative permittivity could be achieved by aligning metallic wires along the direction of a wave whereas negative permeability by placing split ring with its axis along the direction of propagation of wave. The existence of backward waves was discovered before 1967 by Schuster, Pocklington, and Malyuzhinets [45]-[46]-[47]. Materials with negative refractive index were also discovered before Veselago by D.V. Sivukhin [48]-[49], V.E. Pafomov [20], and R. A. Silin [51]. In last few decades, the research is going on this area as it has applications in various fields such as electromagnetics, microwaves [52], antennas, optics, mechanics, acoustics [53], etc..

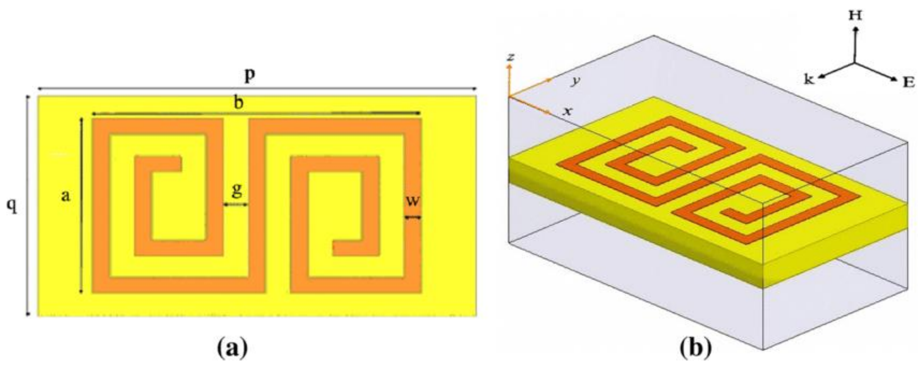


Figure II.28: Example of metamaterial Geometry: (a) 2D unit cells, (b) 3D unit cells [49].

II.7.2- Types of Metamaterial (MTM):

The metamaterials are classified on the basis of permittivity and permeability, as shown in Figure II.29.

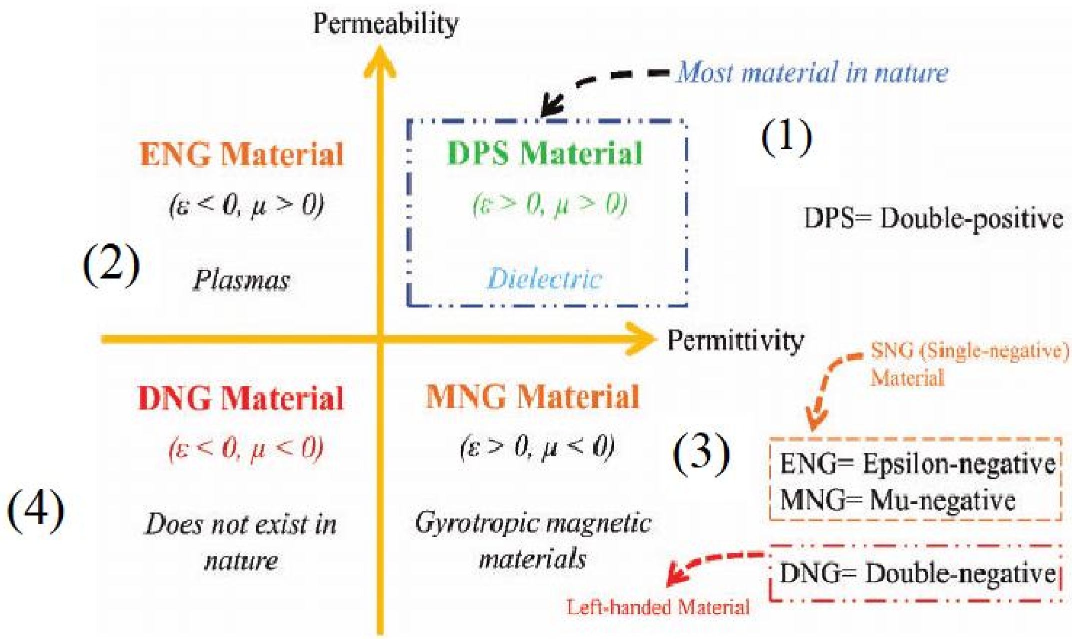


Figure II.29: Classification of Metamaterial on the Basis of Permittivity and Permeability, (1) DPS: Double-positive, (2) ENG Epsilon-negative, (3) MNG Mu-negative, (4) DNG Double-negative [50].

From the previous Figure, we can define the quadrants as follows:

Quadrant 1 (DPS: Double-positive) represents the materials with simultaneously positive value of permittivity and permeability both. It covers mostly dielectric materials.

Quadrant 2(ENG Epsilon-negative) represents the materials with negative permittivity below plasma frequency and positive permeability. It covers metals, ferroelectric materials, and extrinsic semiconductors.

Quadrant 3(MNG Mu-negative) represents the materials with negative permeability below plasma frequency and positive permittivity. It includes ferrite materials.

Quadrant 4 (DNG Double-negative): represents the materials with simultaneously negative value of permittivity and permeability both. No such material is found in nature.

II.7.3-Example of artificial Dielectrics:

The ENG metamaterial uses the metallic mesh of thin wires, for obtaining negative value of ε. These parallel metal wires, which exhibit high-pass behavior for an incoming plane wave, whose electric field is parallel to the wires [51]. The cylindrical array displays the negative permittivity below the plasma frequency, the wire can be made of copper, aluminum, silver, or gold, they are arranged periodically as shown in Figure II.30. The effective permittivity is given by the equation [50]:

$$\varepsilon_{eff} = 1 - \frac{\omega_p{}^2}{\omega^2} \qquad \text{(II.28)}$$

where $\boldsymbol{\omega}$ is the frequency of the propagating electromagnetic wave and $\boldsymbol{\omega_p}$ is the plasma frequency.

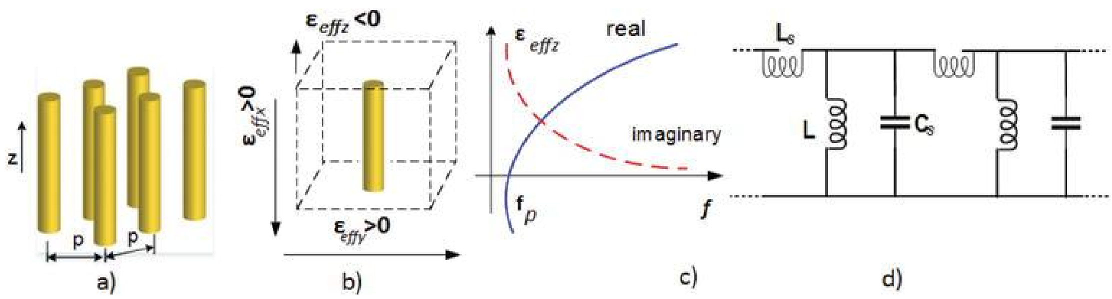


Figure II.30: (a) An array of thin conducting wires , (b) unit cell ,(c) plots of the effective permittivity of an array of wires , and (d) its equivalent circuit [54].

where : **p** is the distance between the axis of cylinders.

Figure (II. 30) shown that when the propagation frequency is below the plasma frequency, its permittivity is negative [52]. This behavior is similar to the propagation of the electromagnetic waves in plasma medium. The propagation frequency as close to the plasma frequency, the value of effective permittivity is increasing. At the plasma frequency, the effective permittivity is equal to zero, and this corresponds to the refractive index equal to zero.

II.7.4- Example of artificial Magnetics:

As the mu-negative (MNG) material, the most popular structure has been using is split ring resonators (SRRs). A unit cell of the SRR is composed of two concentric metallic rings (can be circle or square) and separated by a gap *d* (see Figure II.31). Each ring has a narrow slot and they are spaced 180 degree apart on each side. The gap between inner and outer ring acts as a capacitor, while the rings themselves act as an inductors. Therefore, the combination of the two rings acts as an LC resonance circuit. The effective permeability of MNG metamaterials is given by the formula (II.29):

$$\mu_{eff} = \mu'_{eff} - j\mu'_{eff} = 1 - \frac{f^2{}_{mp} - f^2{}_0}{f^2 - f^2{}_0 - j\gamma f} \qquad \text{(II.29)}$$

where **f** is the frequency of the signal, $\mathbf{f_{mp}}$ denotes the frequency at which (in the lossless case) $\boldsymbol{\mu_{eff}} = \mathbf{0}$ ("magnetic plasma frequency"), $\mathbf{f_0}$ is the frequency at which $\boldsymbol{\mu_{eff}}$ diverges (the resonant frequency of the SRR), and γ represents the losses. The frequencies $\mathbf{f_{mp}}$ and f_0 depend on the lattice constant **(p),** and the geometry parameters of the SRR such as inner and outer radius of the rings, the width of the gap between the rings, and the slit width [53]. The dependence of $\boldsymbol{\mu_{eff}}$ on the frequency is shown in Figure II.31.

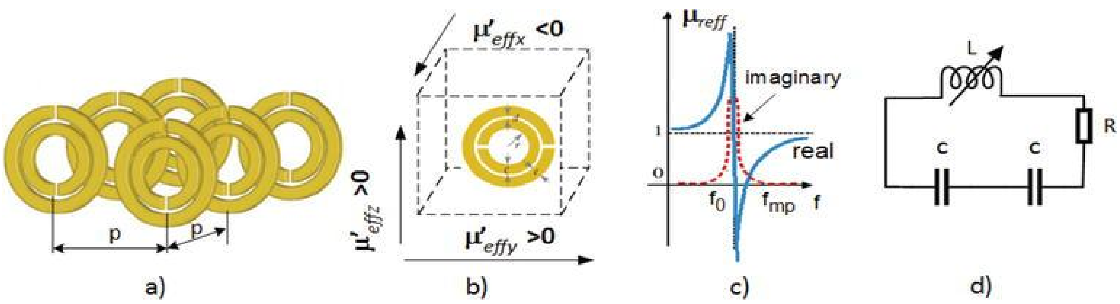


Figure II.31 : An array of SRRs (a), SRR unit cell (b), the effective permeability of SRR array (c), and equivalent circuit (d) [55].

And also the DNG metamaterial is also known as the negative refractive index material (NIM). The properties of the metamaterials DNG were first achieved by combining the thin wire-based ENG structure with SRR-based MNG structure (Figure II.32-a)[54]. This combination satisfies the requirement of $\varepsilon < 0$ from a wire/rodded medium (as an artificial dielectric) and $\mu < 0$ from a split ring resonator (SRR). The first structure was constructed from the combination of planar SRRs etched on a thin dielectric layer and metallic rods (Figure 32-b). In addition, to take advantage of the two sides of the dielectric layers, two-dimensional metamaterials have been designed by engraving the SRR on one side of the dielectric layer and planar strips on the other (Figure 32-c) [56].

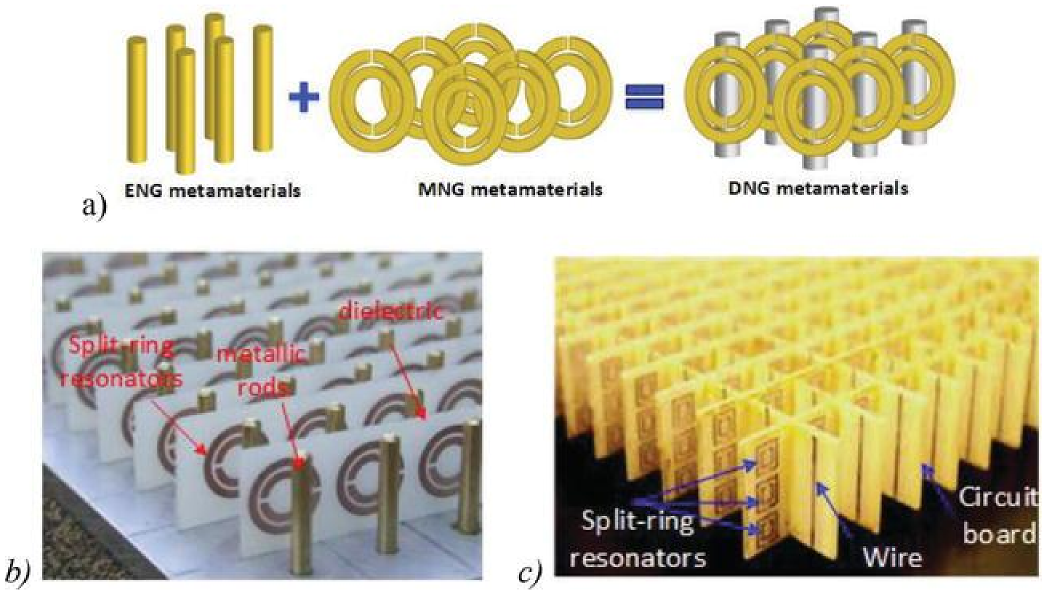


Figure II.32 : Combination of thin wires and SRRs to form DNG metamaterials (a) and examples of realizations of DNG metamaterials (b) and (c) [58].

Because of DNG is made up of thin wire medium and SRRs medium, which their strong resonance behavior (Drude-Lorentz models) affects the frequency. Therefore, the generated DNG metamaterials are also dependent on frequency, which results in the refractive index *n* being reformatted as:

$$n \equiv n_{eff}(\omega) = \sqrt{\varepsilon_{eff}(\omega)\mu_{eff}(\omega)} \quad \text{(II.30)}$$

where $\boldsymbol{\varepsilon_{eff}(\omega)}$ and $\boldsymbol{\mu_{eff}(\omega)}$ are the frequency-dependent effective permittivity and the effective permeability, respectively.

These effective material parameters are characterized by their Drude-Lorentz dispersion models and have the form described in Eqs. (II.31) and (II.32)

$$\varepsilon_{eff}(\omega) = 1 - \frac{\omega^2{}_{ep} - \omega^2{}_{e0}}{\omega^2 - \omega^2{}_{e0} + j\omega\gamma_c} \tag{II.31}$$

$$\mu_{eff}(\omega) = 1 - \frac{\mathrm{F}\omega^2}{\omega^2 - \omega^2{}_{m0} + j\omega\Gamma} \tag{II.32}$$

where $\boldsymbol{\omega_{ep}}$ and $\boldsymbol{\omega_{mp}}$ are the electric and magnetic plasma frequencies respectively, $\boldsymbol{\omega_{e0}}$ and $\boldsymbol{\omega_{m0}}$are the electric and magnetic resonant frequencies, respectively, γ_c is the collision frequency, **F** is an amplitude factor, and **Γ** is a damping factor.

- These expressions have been plotted in Figure II.33.

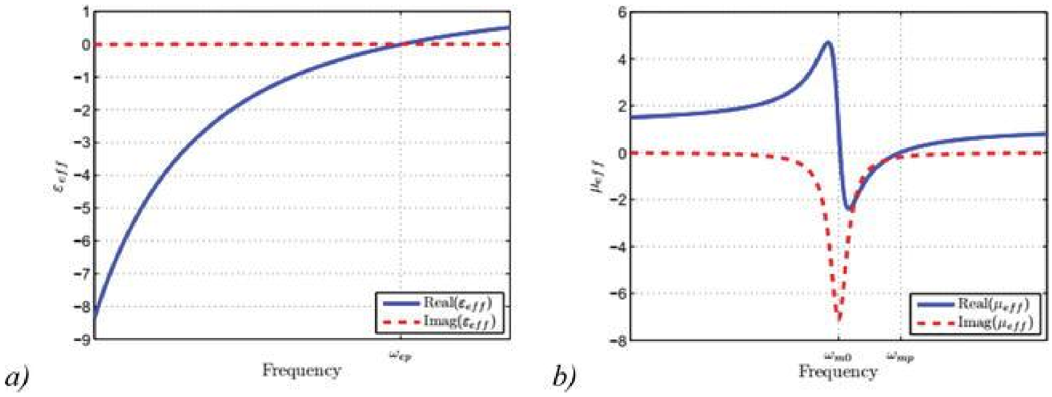


Figure II.33 : Example of The plots of effective permittivity (a) and permeability (b) of the DNG metamaterial [55].

To get the DNG metamaterial from the combination of the ENG and MNG structures, both negative regions of them must coincide. Then, the ENG domain is found corresponding to $\boldsymbol{\omega_{e0}} < \boldsymbol{\omega} < \boldsymbol{\omega_{ep}}$ and the MNG region corresponding to $\boldsymbol{\omega_{m0}} < \boldsymbol{\omega} < \boldsymbol{\omega_{mp}}$. Note that, if the wires are electrically continuous, their resonant frequency is 0 ($\boldsymbol{\omega_{e0}} \approx 0$). This leads to results, since the ENG region is wider compared to the MNG region, the magnetic resonator metamaterial limits the DNG performance, when assembled together with an electric resonator metamaterial.

II.8- Impedance Matching Methods:

The first advantage of impedance matching between the tag antenna and the chip is that it recovers enough energy to generate a DC voltage sufficient to power the RFID chip (in particular the digital processing unit that manages the communication protocol). More adaptation methods can be adopted; the most commonly used being the T-match method and inductive coupling using a loop.

II.8.1- T (T-Match):

T-match is an impedance matching technique for dipole antennas. This type of matching is widely used in RFID-UHF Tags, as it enables the matching between the chip and the Tag antenna at the desired frequency by means of a simple and reliable structure without the need for any additional circuitry. Tag antenna to the desired frequency using a simple, reliable structure, without significantly increasing tag cost or size [58].

The input impedance of a dipole of length ’l’ can be modified by inserting a centered short-circuited stub. The antenna feed will be attached to a second attached dipole of length a ≤ l, positioned at a distance b, separating the two dipoles. The electric current is therefore distributed along the strands of the main dipole according to the size of its cross-sections.

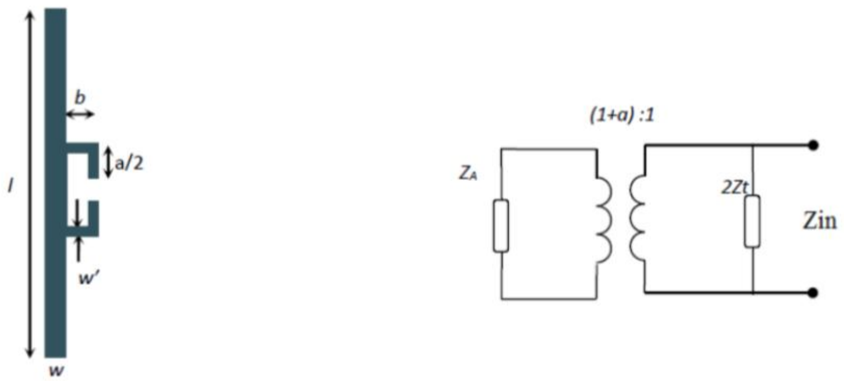


Figure II.34: T-Match configuration and equivalent circuit [54].

Impedance at the supply point can be expressed by the relation (II.33):

$$Z_{in} = \frac{2Z_t(1+\alpha)^2 Z_A}{2Z_t+(1+\alpha)^2 Z_A} \qquad \text{(II.33)}$$

$Z_t = jZ_0 tan\frac{ka}{2}$ is the input impedance of the short-circuit stub formed by the T-match conductors and part of the dipole, $Z_0 \cong 276log_{10}(b/\sqrt{r_e r_e'})$ is the characteristic impedance of the two-conductor transmission line with spacing b; Z_A is the dipole impedance taken at its center in the absence of the T-match connection; r_e = 0.25 w and r_e' = 8.25w' are the equivalent radii of the dipole and of the matching stub, supposed to be planar traces; α = ln(b/r_e')/ln (b/r_e)is the current division factor between the two conductors [56].

II.8.2- The coupled inductance loop:

Instead of the T-match, the radiating dipole may be sourced via an inductively coupled small loop [57], placed in close proximity to the radiating body (Figure II.35). The terminals of the loop area 1 are directly connected to the microchip. This arrangement adds an equivalent inductance to the antenna. The strength of the coupling, W, and therefore of the added reactance, is controlled by the distance between the loop and the radiating body, as well as by the shape factor of the loop.

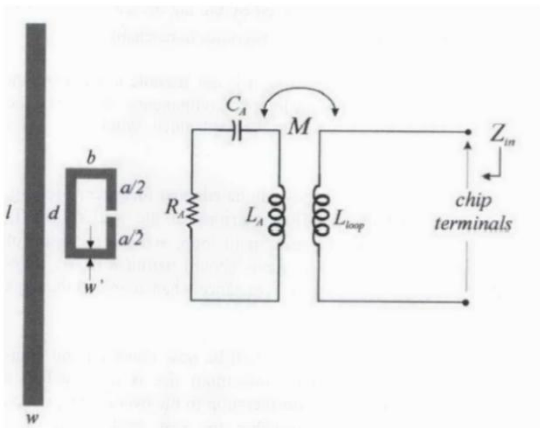


Figure II.35: Inductive coupling adaptation and its equivalent circuit [58].

The inductive coupling can be modeled by a transformer, and the resulting input impedance seen from the loop's terminals is:

$$Z_{in} = Z_{loop} + \frac{(2\pi f M)^2}{Z_A} \quad \text{(II.34)}$$

where $Z_{loop} = j2\pi f L_{loop}$ is the loop's input impedance. Whether or not the dipole is at resonance, the total input reactance depends only on the loop inductance $\boldsymbol{L_{loop}}$ while the resistance is related to the sole transformer mutual inductance, M:

$$R_{in}(f_0) = (2\pi f_0 M)^2 / R_A(f_0) \quad \text{(II.35)}$$

From equation (II.35), we can see that the antenna impedance resistance depends only on the coupling coefficient (M) between the radiating element and the feedback loop.

In equation (II.36), the reactive part depends only on the loop's self-inductance.

$$\mathrm{X_{in}(f_0) = 2\pi f_0 L_{loop}} \quad \text{(II.36)}$$

Conclusion:

In conclusion, effective design and use of antennas require a thorough understanding of antenna parameters, as well as specific considerations related to particular applications such as RFID and miniaturization techniques, such as metamaterials. By leveraging this knowledge, it is possible to create high-performance antennas to respond to the increasing demands of modern communication systems and other related fields.

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Chapter III

Design, Simulation and realization

III.1 Introduction :

The development of miniature antennas is a key requirement for RFID applications in various fields. By reducing the size of RFID components such as tags and readers, we can create more compact and discreet devices. This facilitates easier integration into a variety of objects and products, ranging from retail items to industrial equipment to sensitive documents. Miniaturized RFID tags can be easily concealed within products, packaging, or even documents, providing precise tracking and efficient inventory and supply chain management. Moreover, miniaturization opens up new applications for RFID technology, such as wearable devices and smart clothing, where the size and weight of components are critical considerations. In essence, miniaturization in the realm of RFID paves the way for more discreet, flexible, and integrated solutions for object and product management and tracking.

This chapter presents a new compact microstrip patch UHF-RFID antenna, we will discuss the results of our work and the potential benefits of DGS-metamaterials for miniature RFID antennas in UHF band [1].

III.2 Tag RFID antenna design methodology:

III.2.1- General Design Requirements:

Several general design requirements for RFID antennas are discussed in the following paragraph:

Requirements Analysis:

- Determine the specific application requirements, including size constraints, frequency range, and performance criteria.
- Identify the physical and environmental conditions the antenna will be exposed to.

Initial Design and Simulation:

- Use antenna design software (HFSS) to create an initial design of the microstrip patch antenna.

- Define the substrate material and its properties, such as dielectric constant and thickness.
- Perform simulations to optimize the antenna dimensions and shape for the desired frequency band (UHF).

Incorporation of Metamaterials:

- Simulate the DGS-MTM resonator
- Integrate metamaterial structures into the antenna design to enhance performance characteristics such as gain, bandwidth, and miniaturization.
- Simulate the effects of metamaterials and refine the design accordingly.

Prototype Fabrication:

- Fabricate a prototype of the designed antenna using suitable manufacturing techniques (e.g., PCB fabrication for microstrip antennas).
- Ensure precision in the fabrication process to maintain the integrity of the design.

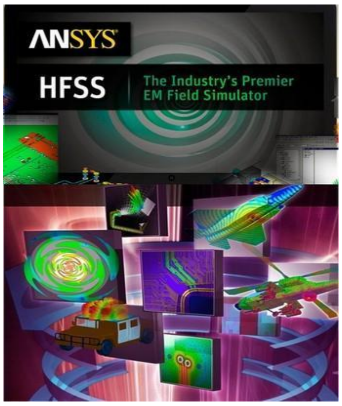
Testing and Measurement:

- Test the fabricated antenna prototype in an anechoic chamber or similar setup to measure the performance parameters of the fabricated antenna prototype (return loss).
- Compare the measured results with the simulated ones to validate the design.

III.3 -Simulation Tools:

The use of electromagnetic (EM) simulation software has become indispensable in the field of antenna design. These tools allow users to analyze the behavior of an antenna before it is even built. In this work, Ansys HFSS 3D electromagnetic simulation software is chosen to simulate new RFID antennas.

- HFSS software:



Ansoft HFSS (High-Frequency Structure Simulator) has evolved over the years with input from many users and industries. It is the tool of choice in industry for high-productivity research, development, and virtual prototyping [2].

HFSS is a high-performance full-wave electromagnetic (EM) field simulator for arbitrary 3D volumetric passive device modeling that takes advantage of the familiar Microsoft Windows graphical user interface, and it's an interactive simulation system whose basic mesh element is a tetrahedron. This allows for the quick and accurate solving of complex 3D geometries, especially those with intricate curves and shapes. Ansys pioneered the use of the Finite Element Method (FEM) for EM simulation. HFSS can be used to calculate parameters such as S-Parameters, resonant frequency, and EM Fields [3].

The fundamental concept of the Finite Element Method (FEM) involves subdividing, or meshing, a structure into small finite elements. A solution for the entire structure is obtained when these interdependent field solutions satisfy the boundary conditions across each inter-element boundary. This approach allows for a highly detailed and accurate representation of complex structures.

This research work utilized Ansys HFSS as the primary tool for simulating and optimizing various RFID antenna structures. As powerful 3D electromagnetic simulation software, HFSS proved invaluable in analyzing antenna performance and identifying areas for improvement.

For our RFID system, we decided to use a patch antenna since it has unique qualities that are suitable for our use case. Patch antennas, like RFID tags, are perfect for integration into gadgets and small areas because of their compact and space-saving form. Additionally, their flat design makes installation easier on a variety of surfaces, including packaging and flat surfaces. Furthermore, the directional properties of patch antennas provide improved electromagnetic field concentration, enhancing RFID tag detection accuracy and reading range. We were able to maximize the overall performance of our RFID solution by choosing a patch antenna for our system, which has the advantages of compactness, efficiency, and ease of integration.

III.4 Evolution of proposed RFID Antenna Design:

III.4.1 Single Split Ring shape antenna:

In the modeling of a microstrip antenna in HFSS, it is common to represent the structure with three main layers (Figure III.1- a): the bottom ground plane, the dielectric substrate, and the radiating element. The bottom ground plane, also known as the ground plane or ground layer, serves as a return conductor for the antenna current, thus contributing to the polarization and overall performance of the antenna. Just below is the dielectric substrate, which may consist of materials such as FR4 or RO4003, providing structural and electrical support to the antenna. Finally, the radiating element, typically a thin strip of conductive material, is positioned on the substrate and is responsible for transmitting or receiving electromagnetic signals. This three-layer structure is crucial for the accurate design and simulation of the antenna's electromagnetic performance in HFSS, enabling users to effectively analyze and optimize its radiation characteristics, gain, and bandwidth [4].

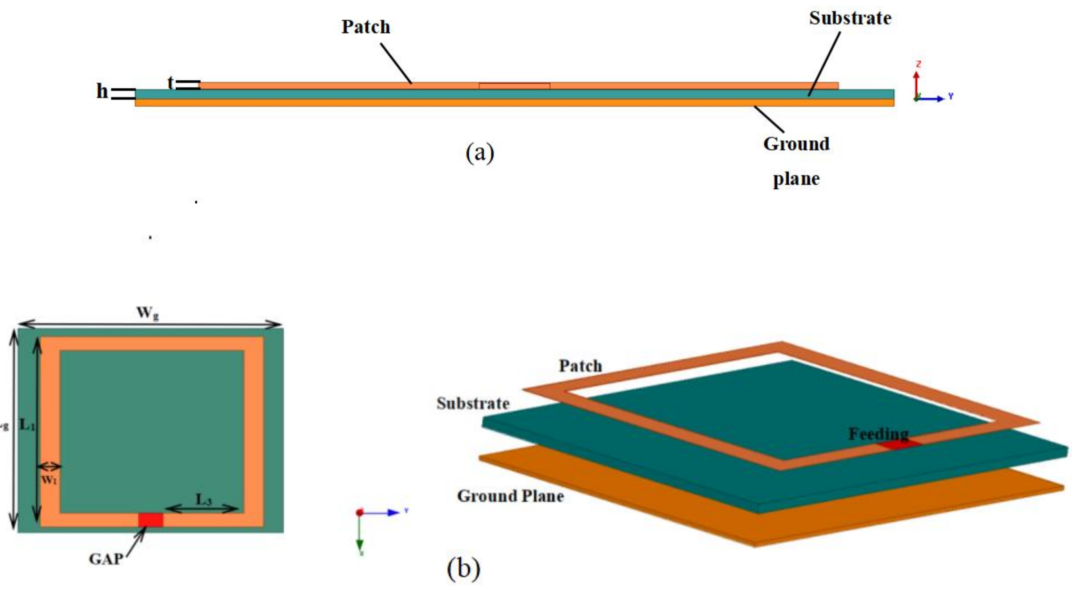


Figure III.1: Geometry of Single Split Ring antenna (a) side view, (b) top view.

The proposed antenna consists of single split ring shape geometry on one side of dielectric, with a ground plane on the other side (Figure III.1-b). The antenna is designed on an FR-4 substrate having a thickness h =1.6 mm, a relative dielectric constant ε_r =4.4, and tangent losses tan(δ) = 0.02. The overall size of the proposed antenna is 108 mm × 86.6 mm and the metallization thickness is 35 µm. The operating frequencies of the antenna is f = 0.915 GHz. Furthermore, a lumped port with 50 ohm impedance is employed to feed the proposed antenna. The first step in the design involves calculating the dimensions of the single rectangular ring using equations based on the resonance frequency of 0.915 GHz and the dielectric constant of the FR4 substrate $\varepsilon_r = 4.4$ [5].

The width of the patch is calculated as follows:

$$W_p = \frac{c}{2f}\sqrt{\frac{2}{\varepsilon_r+1}} \quad \text{(III.1)}$$

The effective permittivity is expressed as:

$$\varepsilon_{eff} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\left[1 + 12\,\frac{h}{W_p}\right]^{-1/2} \quad \text{(III.2)}$$

The length of the patch is determined by:

$$L_p = 0.824\,h\left[\frac{(\varepsilon_{eff}+0.3)(\frac{w}{h}+0.264)}{(\varepsilon_{eff}-0.258)(\frac{w}{h}+0.8)}\right] \quad \text{(III.3)}$$

Since the ground plane and the substrate share identical dimensions, their sizes can be calculated using the following equations [5]:

$$Wg = W_p + 6 \times h \quad \text{(III.4)}$$

$$Lg = L_p + 6 \times h \quad \text{(III.5)}$$

The initial dimensions of the propose antenna, illustrated in Figure III.1.b (step 01), are as follows:

Ground and substrate: W_g = 108 mm and L_g = 86.6 mm.

Patch: W_p = 99.6 mm and L_p = 77.7 mm.

Various optimizations have been implemented to decrease these dimensions. With carefully placed gaps until achieving the best results (Figure III.2).

To achieve optimal performance of our proposed antenna, we went through a few steps (iterations). We have summarized the most important steps in Figure III.2. In the initial step, we introduced a single copper rectangular ring while maintaining the antenna's initial dimensions (108 ×86.6 mm^2). Subsequently, we modified the dimensions of the rectangular ring in step 2. In the next step, we further optimized the antenna by introducing a change in the shape of the gap in the rectangular ring and adjusting its dimensions to enhance miniaturization and improve performance. These iterative adjustments were made until approaching the desired RFID frequency in the final step.

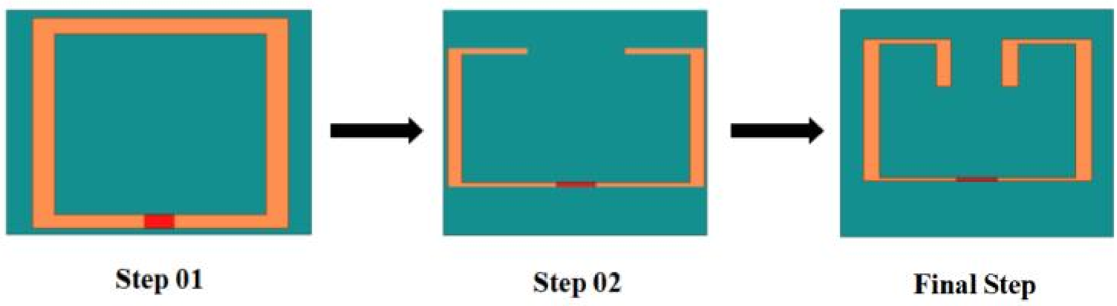


Figure III.2: Steps for the design of proposed antennas.

The geometry and specifications of the antenna parameters for the final design step are illustrated in Figure III.3 and Table III.1, respectively.

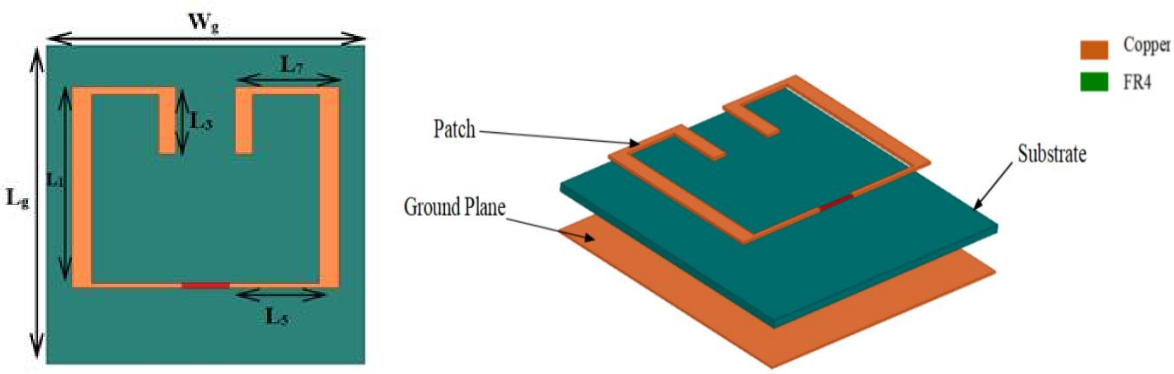


Figure III. 3: Geometry of the final step antenna.

Parameter	Value (mm)	Parameter	Value (mm)
L_g	81	t	0.035
W_g	81	h	1.6
L_1	48	L_3	17
L_7	22	L_5	28

Table III.1: The dimensions of the final iteration of the proposed antenna

A commercial tool, Ansoft High Frequency Structure Simulator (HFSS), is used to simulate the proposed antennas. Figure III.4 shows the return loss of the three steps in the evolution of the antenna, wherein a successful band is observed with the characteristics of the S_{11} value of -12 dB at 0.928 GHz obtained in the final step.

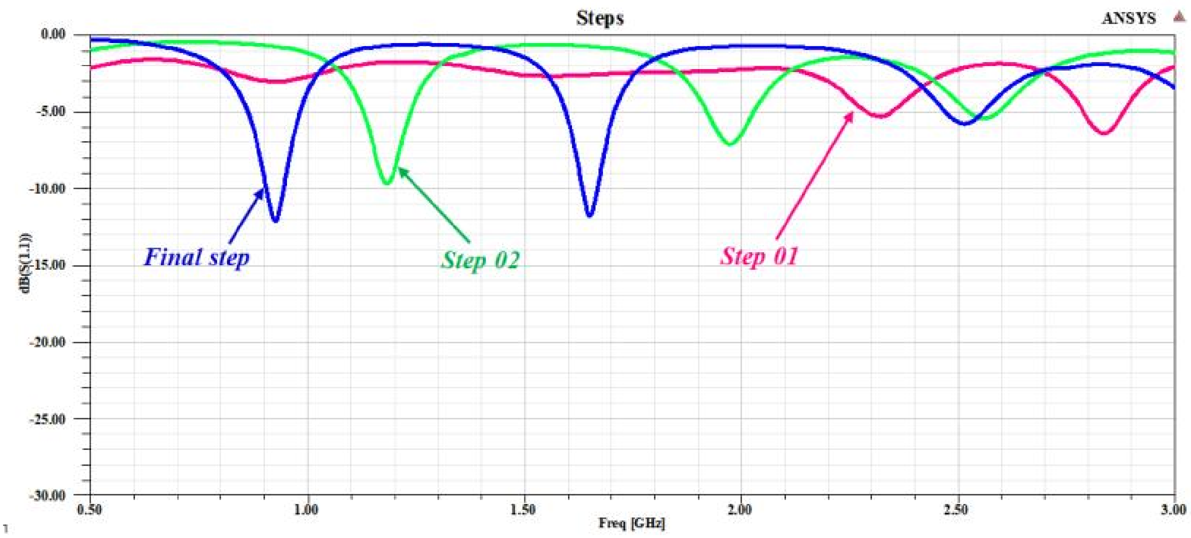
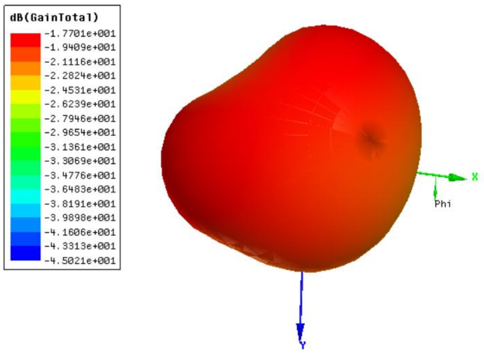
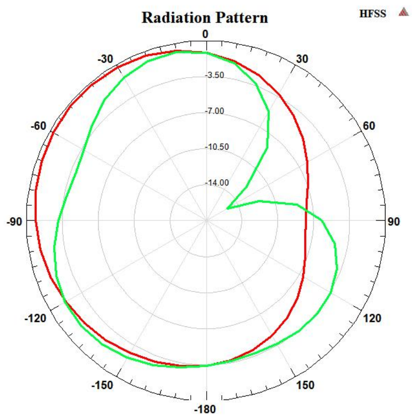


Figure III.4: Return losses of three steps of design.

At 0.928 GHz frequency, radiation patterns and simulated gain of the antenna in final step are depicted in Figure III.5. The results suggested a severe degradation of the gain (-17.7 dB).





(a) **(b)**

Figure III.5: Simulated results, (a) Gain of Antenna, (b)Radiation Pattern and at 0.928 GHz.

✧ Parametric study of the partial ground:

The purpose of this section is to illustrate the effect of partial ground on the electrical performance of the RFID antenna such as the gain and the reflection coefficient S_{11}. All simulations are achieved using Ansys HFSS software.

By analyzing different parameters, we were able to identify key areas of improvement to optimize overall performance. This study allowed us to understand how each adjustment affects the antenna response and guided us in implementing precise modifications to achieve better results.

The effect of modifying the width W on the antenna results in terms of reflection coefficient, radiation Pattern and gain has been studied. The initial step involves starting with a fully grounded plane with a width W of 81 mm, as depicted in Figure III.3. This width varies From 75 to 15 mm with a decrease of 15 mm (Figure III.6).

Figure III.7 displays the results of the *S*-parameters with various values of W. It is obvious from the obtained results that the first and second operating frequencies are more affected by the parameter W (75 mm and 60 mm). The RFID antenna has two resonant frequencies around 0.916 GHz and 1.65 GHz. The optimal configuration for the ground plane is found with a width of "W = 60 mm", it has three bands around:0.929 GHz, 1.65 GHz and 2.449 GHz .The step 3 result yielded a good S-parameter of -30.7 dB at 0.929 GHz.

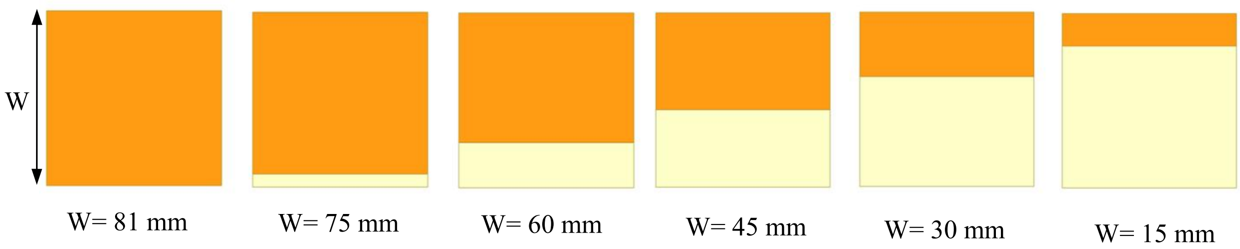


Figure III.6: Partial ground design of the proposed antenna with its different values of width (W).

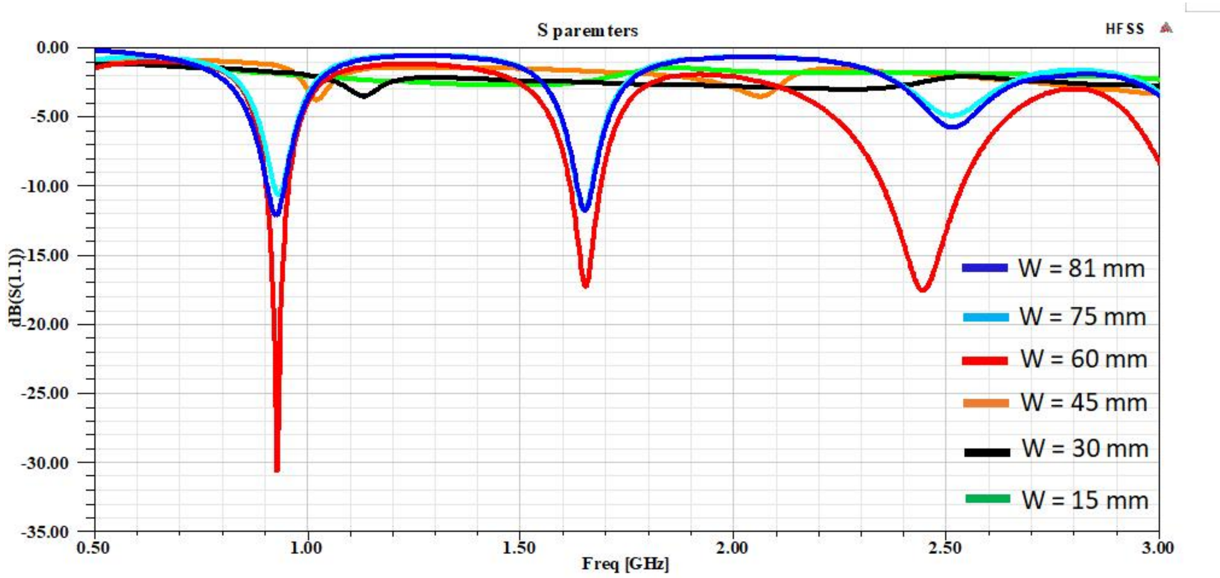


Figure III.7: Result of the *S*-parameters for different values of W.

III.4.2 S-shape folded meander-line antenna:

In the following study, a modified meander shape microstrip patch antenna has been proposed for RFID applications around 0.915 GHz band. Figure III.8 shows the shape of the suggested tag antenna, which has a size of $80 \times 80 \times 1.6$ mm³.

To improve the antenna's performance, the design is comprised of an S-shape meander line and it is fed via lumped port. The structure is implemented on an FR4 Epoxy substrate with a dielectric constant ϵ_r= 4.4, a loss tangent tan (δ) = 0.02, and a thickness h equal to *1.6 mm*. The patch was designed with copper material with a thickness of 0.035 mm and a partial ground on the opposite side of the antenna.

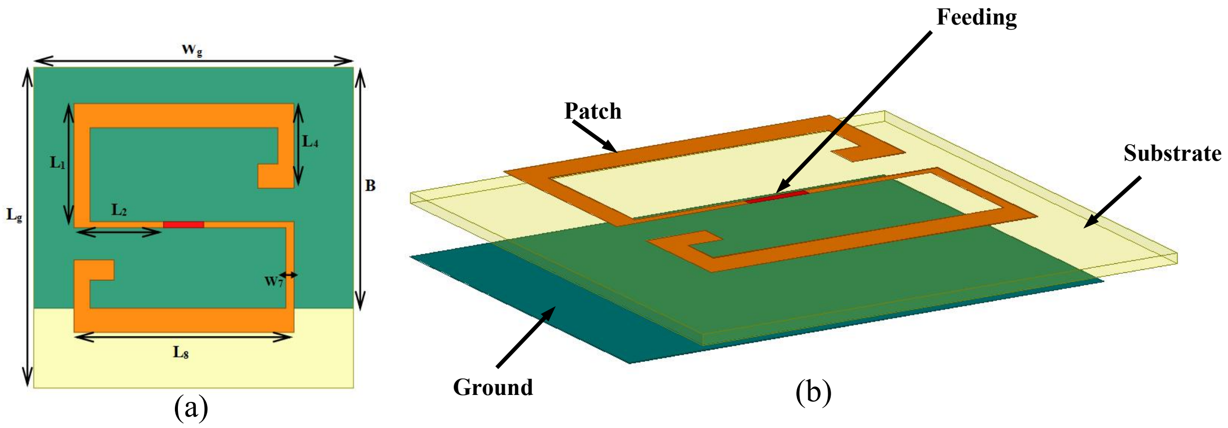


Figure III.8: S-shape folded meander-line antenna, (a) In two-dimensional view, (b) In three-dimensional view.

The antenna is optimized by using HFSS Simulator and the final dimensions are illustrated in Table.III.2.

Parameter	Value (mm)	Parameter	Value (mm)
L_g	80	t	0.035
W_g	80	h	1.6
L_1	23.5	L_4	15
L_2	22.5	B	60
W_7	2	L_8	55

Table III.2: Dimensions of the proposed antenna of Figure III.8.

The return loss for the proposed antenna was obtained using HFSS, and is illustrated in Figure III.9.

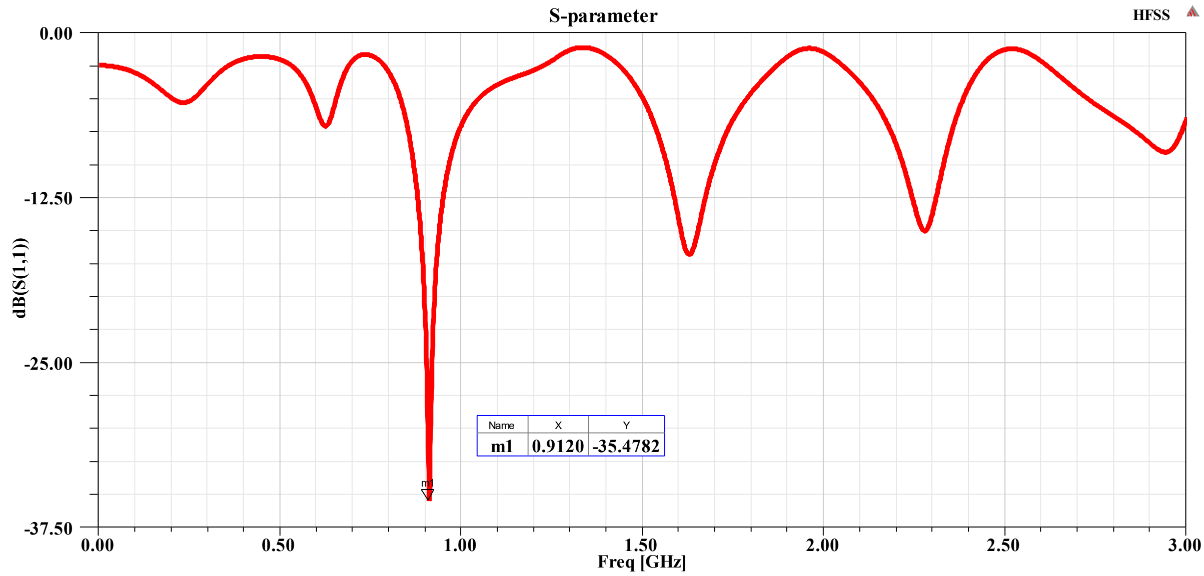


Figure III.9: Return loss of the S-shape folded meander-line antenna.

The 2D radiation pattern at E and H planes, and the simulated gain at 0.912 GHz are illustrated in Figure III.10.

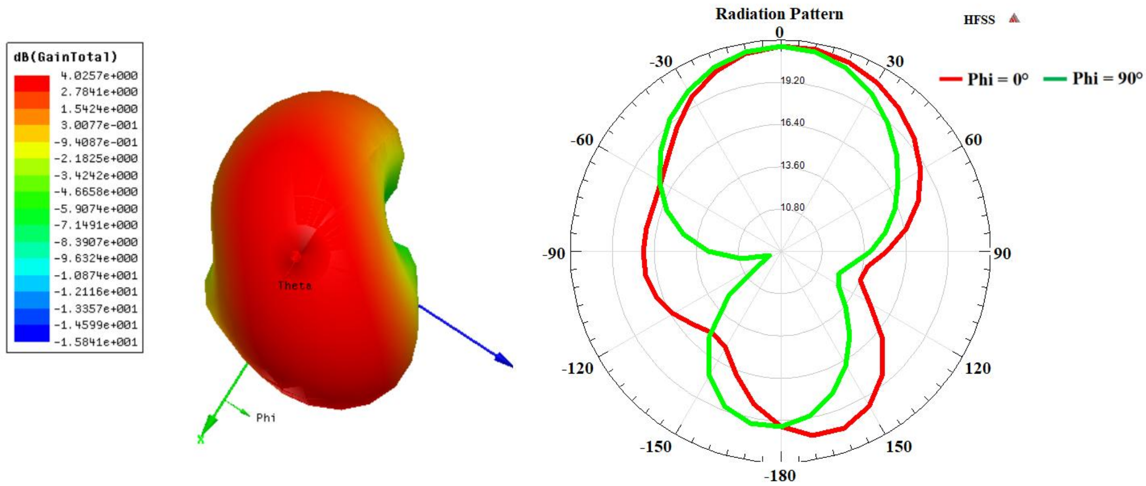
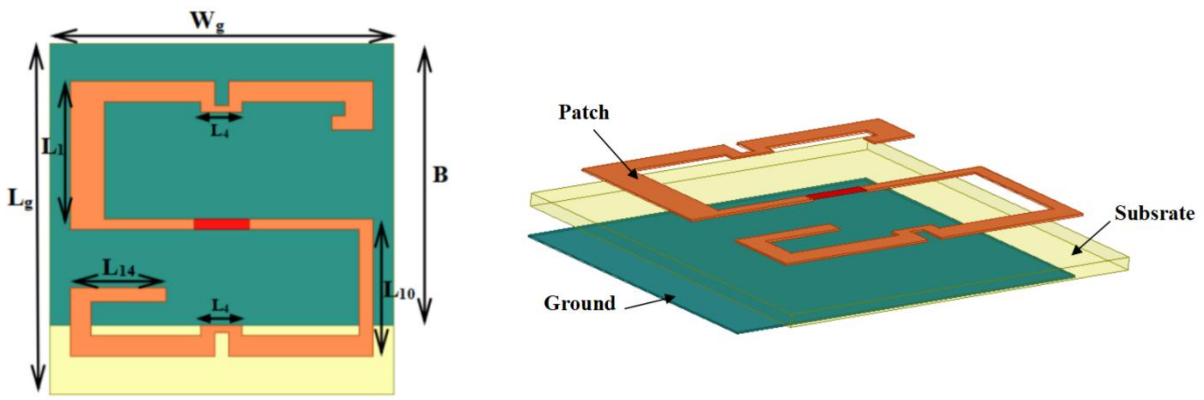


Figure III.10: Radiation patterns and gain for the proposed RFID antenna at 0.912 GHz

E-plane , H-plane.

We notice an improvement in performance in terms of gain (4.02 dB) and reflection coefficient (less than -35 dB).

In the continuation of this work, we will focus more on the miniaturization of the proposed antenna by using folded asymmetric meander-line technique (Figure III.11).



(a) (b)

Figure III.11: Geometry of folded asymmetric meander-line antenna, (a) Top view and (b) Three-dimensional view.

After optimization, the final dimensions are illustrated in Table III.3.

Parameter	Value (mm)	Parameter	Value (mm)
L_g	51	t	0.035
W_g	50	h	1.6
L_1	20	L_4	6
L_{10}	18	B	41
L_{14}	14		

Table III.3: Dimensions of the suggested RFID antenna.

Figures III.12 and III.13, show the simulated return loss, the 2D radiation pattern at E and H planes and gain of the proposed antenna, respectively.

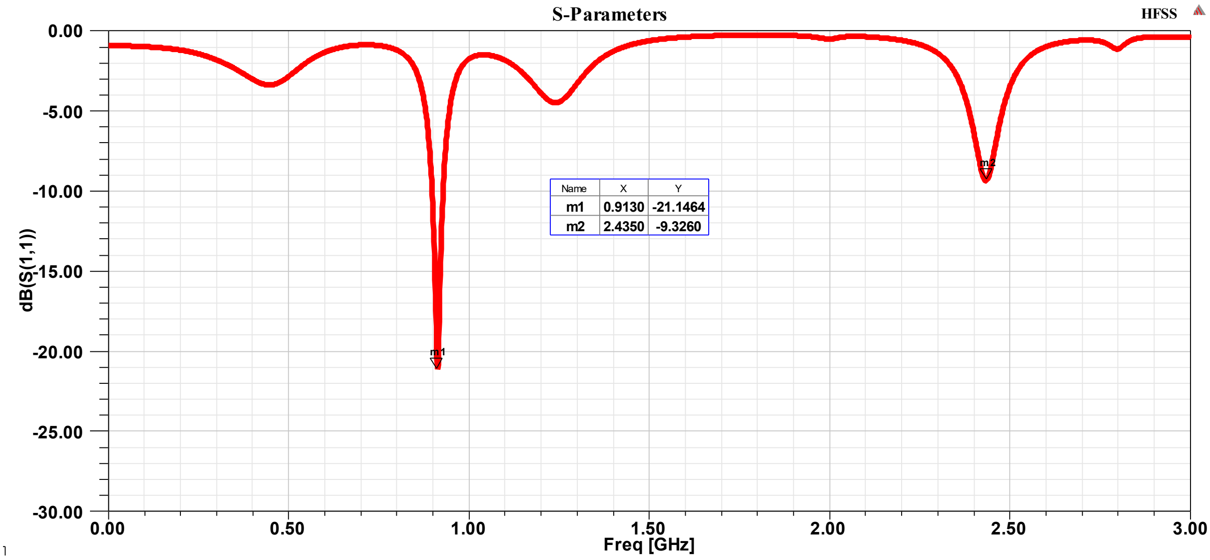


Figure III.12: The S_{11} parameter of the proposed antenna.

It can be seen from Figure III.12 that the S_{11} is -21 dB with a frequency of 0.913 GHz and another peak around 2.45 GHz; also, the bandwidth for |S-parameters| less than -10 dB) is about 35 MHz for first peak.

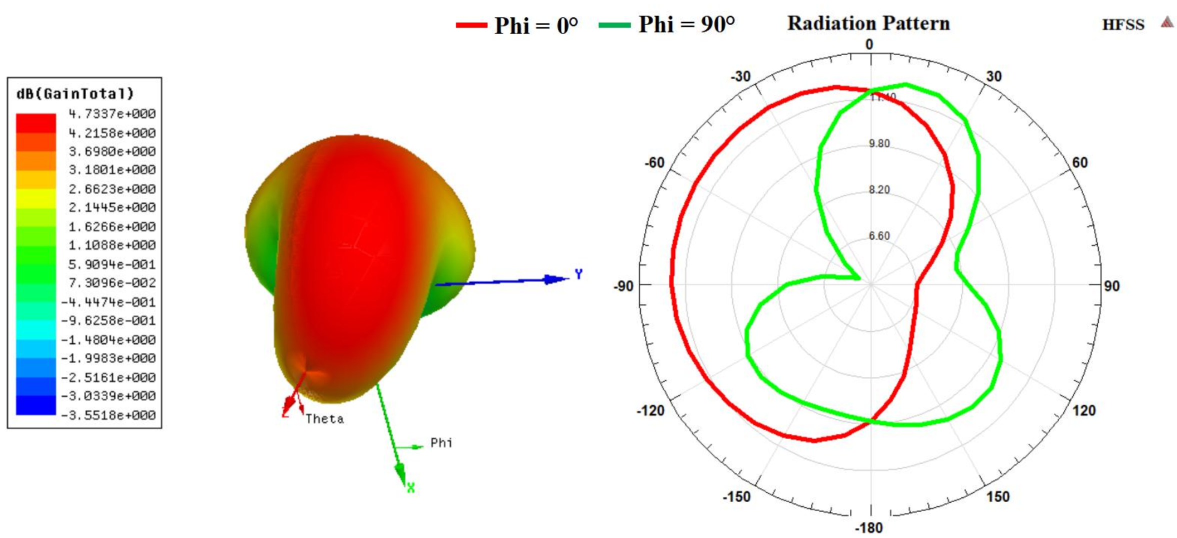


Figure III.13: The 3D gain and radiation pattern of the proposed antenna at 0.913 GHz.

In this study, we embarked on a process of miniaturization of the previous structures, aiming to reduce its dimensions while preserving its efficiency and functionalities. This classical miniaturization technique allowed us to explore new shapes and configurations, giving remarkable results. By compressing the components and rethinking the dimensional aspects, we have succeeded to miniaturize the antennas, while achieving the desired performance. The advantages of this miniaturization are multiple, offering increased flexibility in integration into systems while maintaining a high level of performance and efficiency.

III.5 Structure and design evolution of the RFID metamaterial antenna:

The metamaterial is described as an artificial material with extraordinary properties that is not available in nature. The metamaterial structure offers numerous potential benefits, such as in the enhancement of performance and minimization of the overall dimensions. Most metamaterial types, have high Q factor, which is suitable to produce narrowband resonator. This narrowband resonator is capable to enhance data capacity of chip-less RFID by maximizing the number of resonators within specific frequency range. In this context, we propose a new resonator for designing compact RFID antennas.

III.5.1 Metamaterial double-rings hexagonal closed resonator loaded dumbbell-shaped (unit cell):

In our current study, we employed a unit-cell consisting of a double-ring hexagonal resonator, wherein both the outer and inner rings are closed. These unit cells are loaded with two dumbbell-shaped structures, as illustrated in Figure III.14.

The simulation of the antenna is done by using High Frequency Structure Simulator (HFSS).

Perfect magnetic conductor (PMC) boundaries are applied along the X-axis, while perfect electric conductor (PEC) boundaries are applied along the Y-axis. As seen in Fig.III.14-(b), electromagnetic waves travel along the Z-axis through ports 1 and 2, which are perpendicular to the boundaries of PMC and PEC. The resonator value parameters are d = 6.69 mm, L = 5.8 mm , K=3.34 mm, a = 0.6 mm, and K_0 = 2.30 mm, b = 0.9 mm, d_0 =4.6 mm.

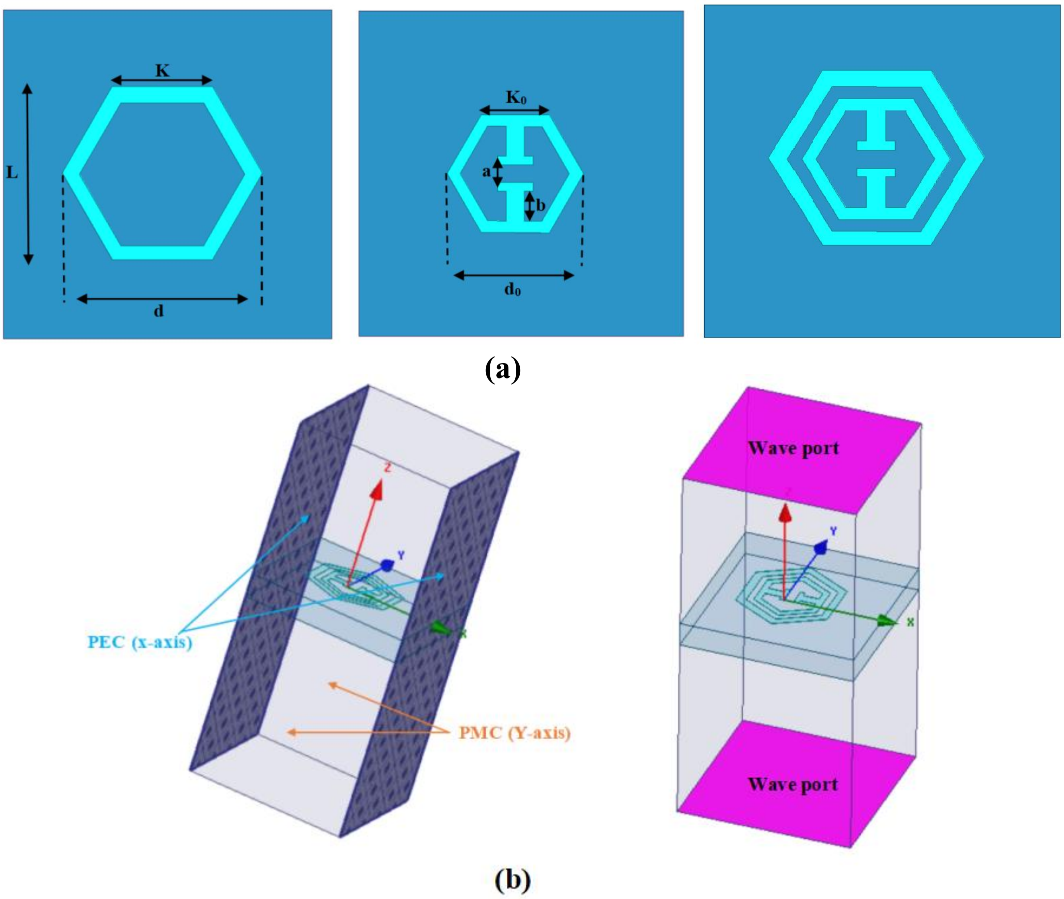


Figure III.14: The suggested metamaterial unit cell structure: (a) schematic of the MTM – double rings Hexagonal resonator (b) 3D unit cell.

To prove the presence and effect of metamaterial in the proposed resonator, the Nicolson Ross Weir (NRW) method is used to extract the effective parameters of the MTM: permeability, permittivity, and refractive index [6].

- This method uses the following equations:

$$V_1 = S_{21} + S_{11} \quad \text{(III.6)}$$

$$V_2 = S_{21} - S_{11} \quad \text{(III.7)}$$

$$\mu_{eff} = \frac{2}{(jK_0 d)} \frac{(1-V_2)}{(1+V_2)} \quad \text{(III.8)}$$

$$\varepsilon_{eff} = \frac{2}{(jK_0 d)} \frac{(1-V_1)}{(1+V_1)} \quad \text{(III.9)}$$

$$n_{eff} = \sqrt{\mu_{eff} \times \varepsilon_{eff}} \quad \text{(III.10)}$$

$\mathbf{K_0}$ is wave number in free space, $\mathbf{K_0} = \frac{\omega}{c}$

ω is the angular frequency, and c is the speed of light in free space: $C=3 \times 10^8$ m/s.

d: the thickness of the substrate.

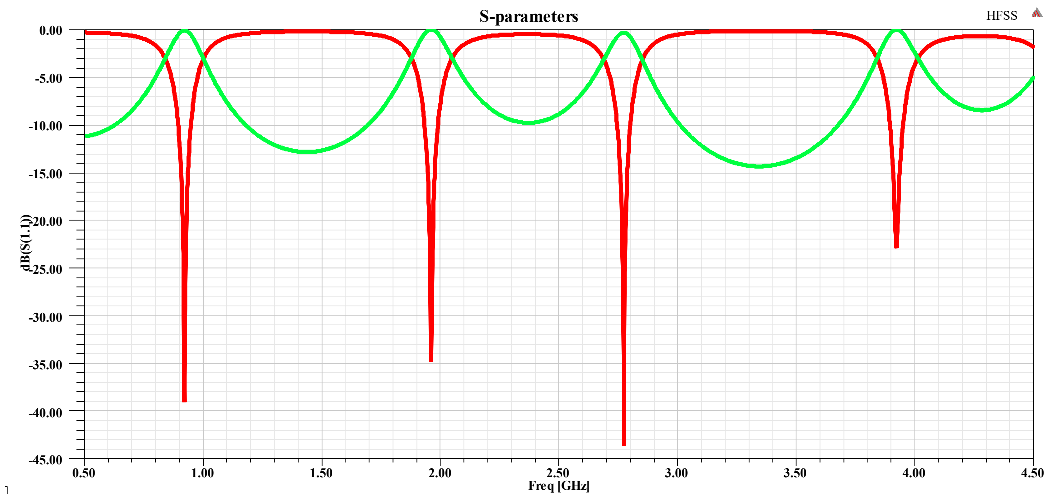
S_{11}, S_{21}: the S-parameters.

ε_{eff} and μ_{eff} are effective permittivity and effective permeability.

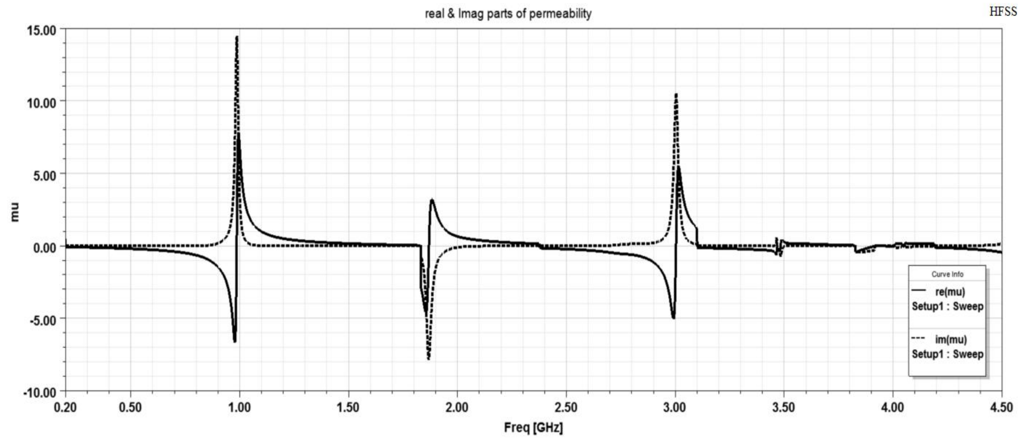
n_{eff} is the refractive index.

Figure III.15.a illustrates the refection coefficient S_{11} and the transmission coefficient S_{21} of the proposed resonator as a function of frequency. From the S-parameters, we extracted the values of permeability as shown in Figure III.15.b.

The results in term of permeability against frequency are reported in Figure III.15.b , We can clearly observe that the proposed metamaterial resonator presents a negative region around the first RFID frequency band around 0.923 GHz which proves the metamaterial effect of the proposed structure.



(a)



(b)

Figure III. 15: The MTM resonator results: (a) S-parameters (S_{11}, S_{21}), (b) the real and imaginary part of the permeability.

III.5.2 MTM Antenna design loaded DGS-CRHCRs resonators:

Based on our previous designs, we chose the meander-line asymmetric folded antenna shown in Figure III.11 to load with MTM resonators due to its high performance results. The geometry of the designed metamaterial resonator is presented in Figure III.14. It consists of folded asymmetric meander-line (Figure III.11) on the front side of the Frame Resistant substrate having relative permittivity of 4.4, tangent loss of 0.02, the substrate thickness is 1.6mm and, the conductor thickness is 0.035mm. The antenna has a partial ground on the opposite side.

To reduce the size of the antenna, metamaterial unit cells formed by complementary double-ring hexagonal resonators are etched into the ground plane. The designed antenna is excited by a lumped port with characteristic impedance of 50 Ω. The antenna is optimized by using HFSS software.

A complementary double-ring hexagonal closed resonator loaded dumbbell-shaped (CRHCR) structure is introduced, which is the negative image of the typical double-ring hexagonal closed resonator (RHCR).These cells are typically placed on the ground plane of the antenna to adjust the electromagnetic properties of the surrounding environment. CRHCRs act as resonant structures or Defected Ground Structure (DGS), that help optimize the antenna's frequency response, reduce losses, and improve the overall efficiency of the RFID system. By adjusting the geometry and properties of CRHCRs, it is possible to achieve optimal performance in terms of directivity, gain, and antenna bandwidth for RFID applications [7].

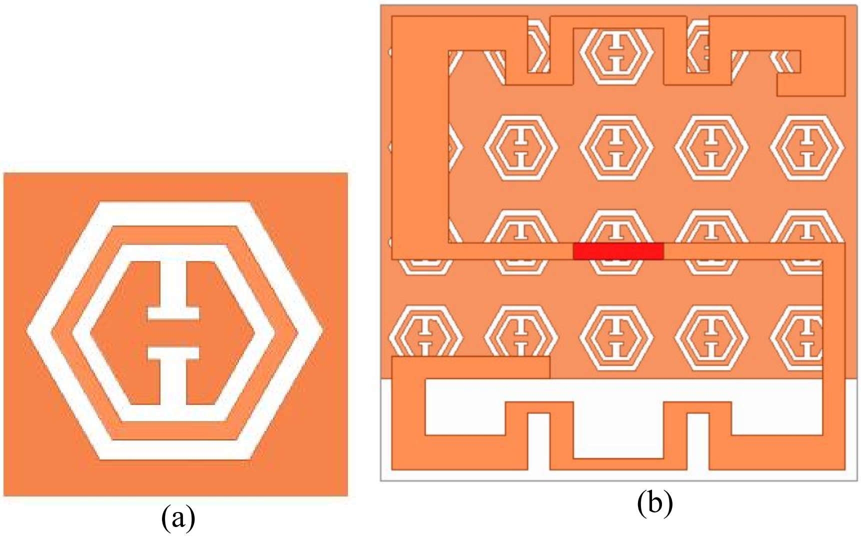


Figure III.16: Proposed MTM antenna structure, a) CRHCR resonator, b) Antenna loaded CRHCRs resonator.

III.5.2.a Iterations of the designed MTM Miniaturized antenna:

At the design stage, the proposed antenna underwent several iterations to achieve better characteristics, as illustrated in Figure III.17. The initial iteration of the proposed antenna started with the design of an S-shaped meander antenna loaded with one resonator, as depicted in Figure III.17.a. Subsequently, the design was modified with the addition of two resonators to enhance performance, as shown in Figure III.17.b. Further modifications included the placement of two additional resonators, as presented in Figure III.17.c. Finally, the antenna was restructured by positioning nine or more metamaterial resonators on the partial ground surface, as shown in Figures III.17.d and III.17.e. These metamaterial resonators consisted of CRHCR resonators.

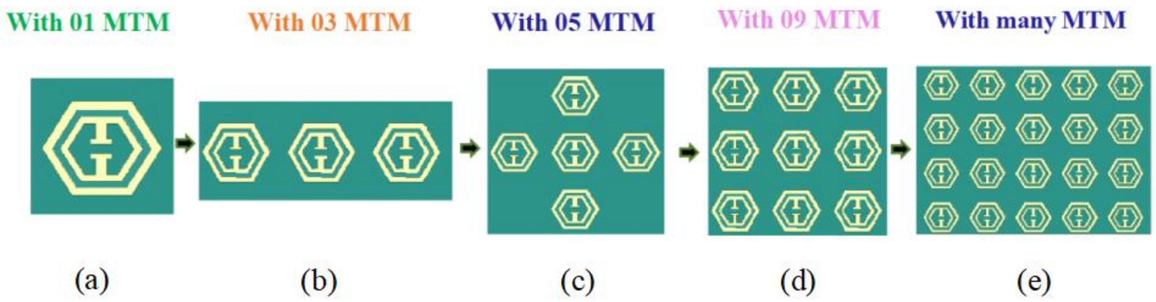


Figure III.17: The back view of the proposed antennas with ground plane periodically etched by CRHCRs resonators: a) Iteration 1, b) Iteration 2, c) Iteration 3, d) Iteration 4, e) Iteration 5.

a)-Antennas with One CRHCR "Iteration 1":

The metamaterial resonator is a key element to achieve antenna miniaturization. The first iteration has a miniature size of 48 mm x 47mm x 1.6 mm and good performance (Figures III.18, III.20 and III.21). We compared these results with those obtained with conventional antenna (Figure III.11).

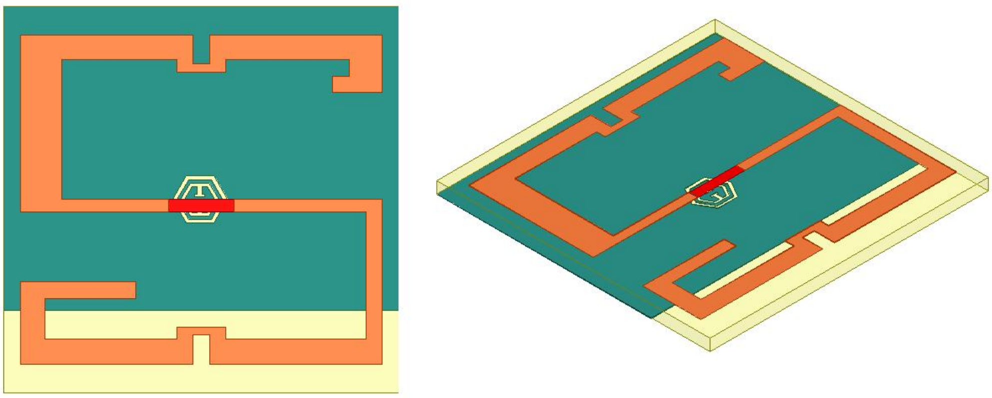


Figure III.18: Structure of proposed antenna with one CRHCR.

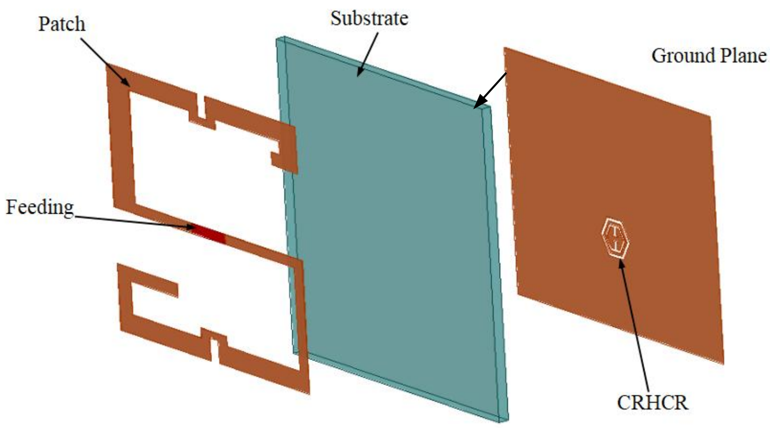


Figure III.19: Different layers of the RFID antenna with one CRHCR.

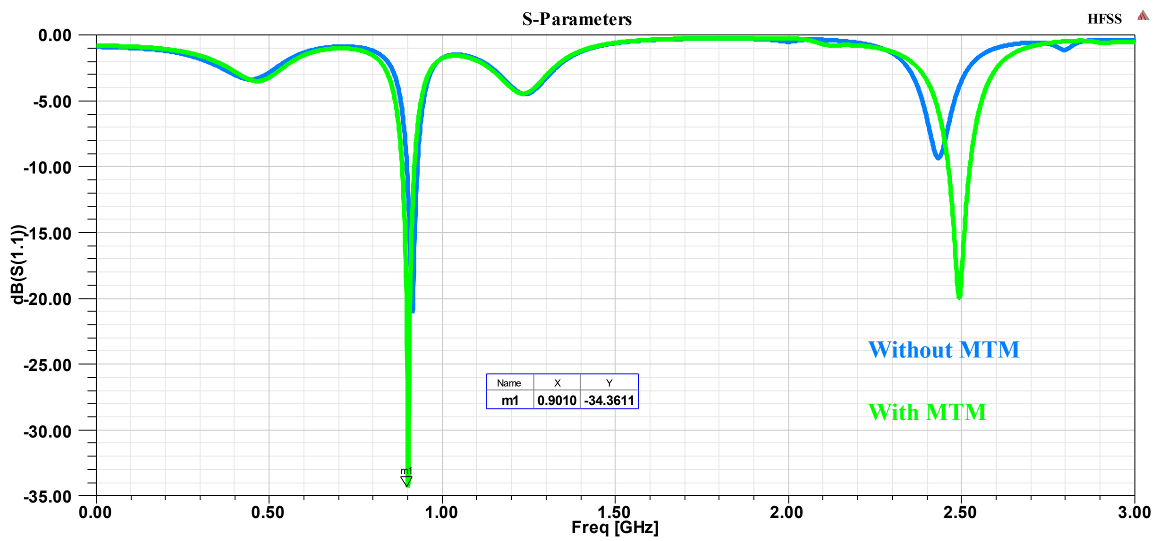
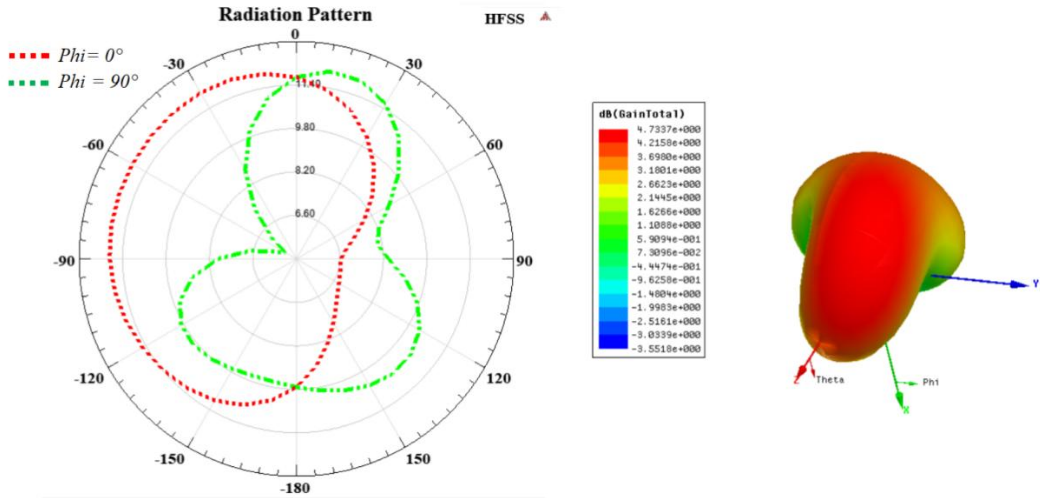
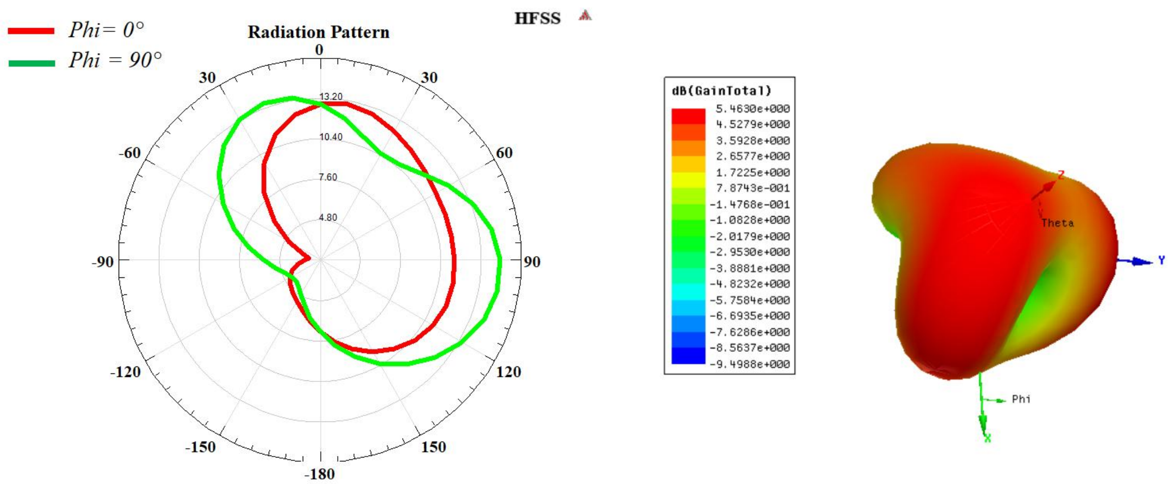


Figure III.20: Comparison of the simulated return losses between the conventional antenna and the antenna loaded with one CRHCR.



(a)- Without MTM



(b)-With MTM

Figure III. 21: The radiation patterns and 3D gains of iteration 1 at 0.9 GHz, (a) Without MTM, (b) With MTM

We observe that this antenna operates in dual-bands at 0.9 GHz and 2.5 GHz. These frequencies correspond to the UHF band and the microwave band, respectively, which are essential for RFID technology.

This structure offers improved isolation at the operating frequencies, with the reflection coefficient reduced to -34 dB at 0.9 GHz and approximately -20 dB at 2.5 GHz. The bandwidth of the first band is around 35 MHz, while the bandwidth of the second band is about 62 MHz.

In the context of Radio-Frequency Identification (RFID) technology, enhancing the gain of an antenna can significantly impact system performance. Transitioning of antenna from a gain of 4.73 dBi to 5.46 dBi in an RFID system can result in improved tag reading at a distance. This enhancement can improve reading reliability, particularly in environments susceptible to interference or obstacles.

b)-Antennas with three CRHCRs "Iteration 2":

In the second iteration, we added two more resonators, as illustrated in Figure III.22.

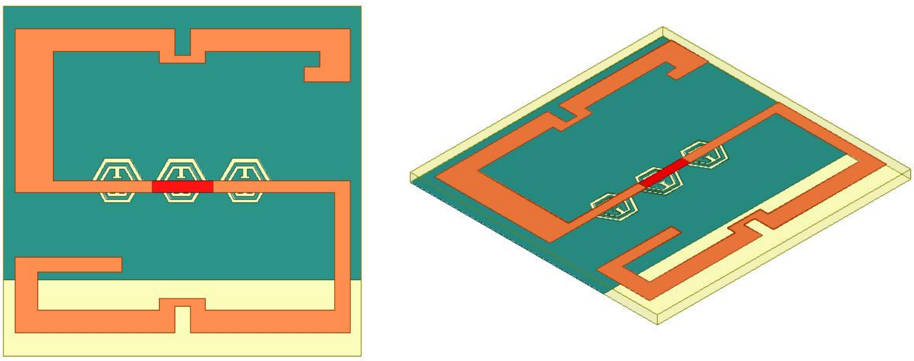


Figure III.22: Structure of proposed antenna with three CRHCRs.

Parametric study:

In the second iteration, we studied the effect of varying distances between the resonators on the antenna's performance in terms of reflection coefficient, gain, and radiation pattern (Figure III.23). The D parameter varies from 1 to 5 mm in 1 mm increments. The results for the S-parameters and radiation pattern of the developed antenna with various values of D are illustrated in the following Figures.

This comprehensive investigation allowed us to determine the optimal spacing that maximizes the performance of the antenna system. By systematically exploring different configurations, we gained valuable insights into the interaction between the resonators and fine-tuned the design for enhanced functionality.

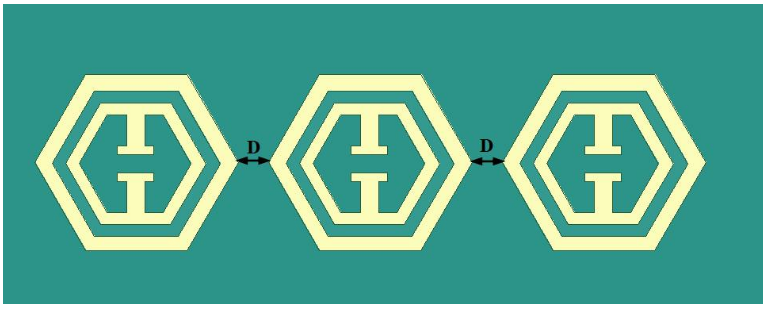


Figure III.23: The back view of the proposed antennas with ground plane periodically etched by three CRHCRs for parametric study.

The following Figure shows the impact of different resonator distances:

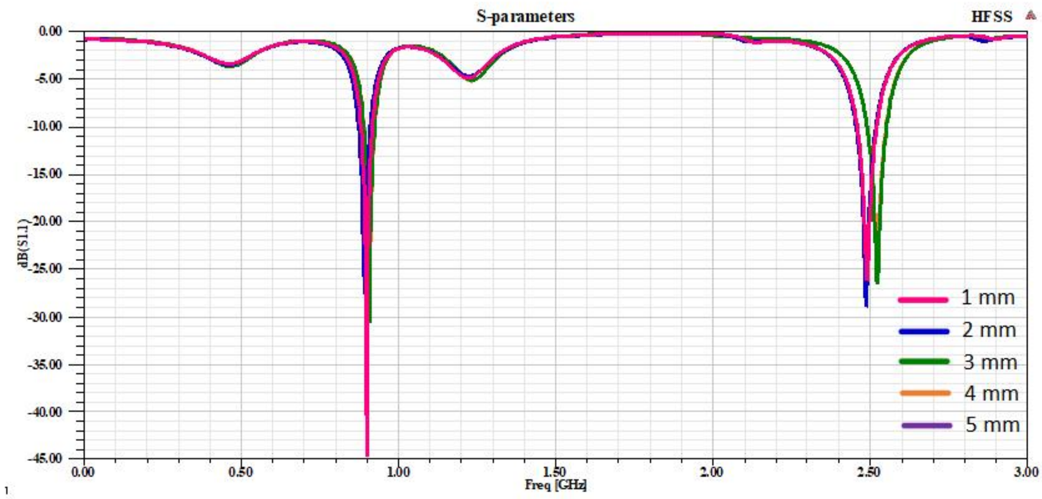
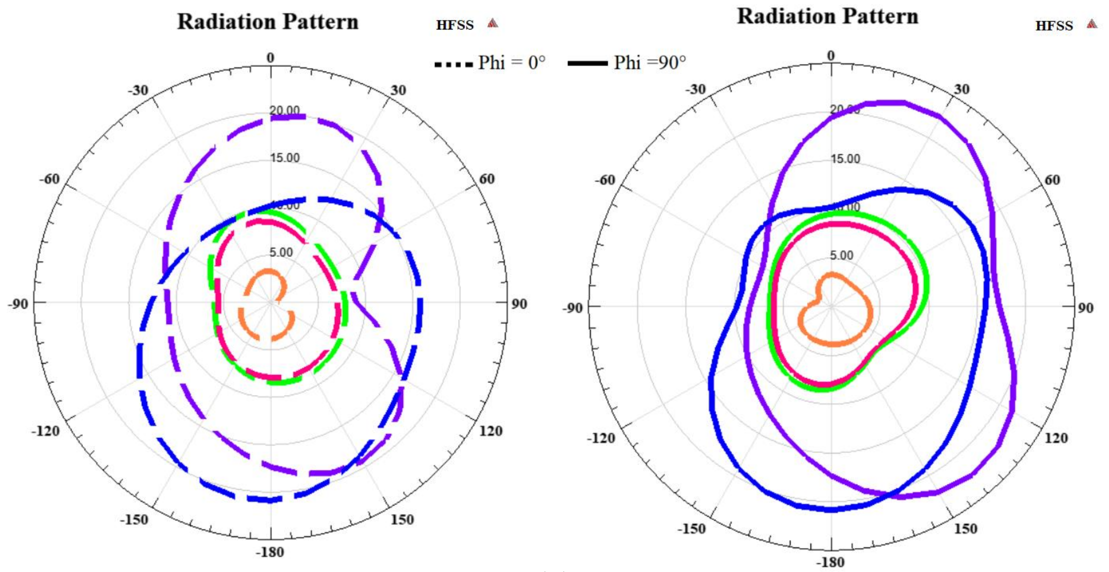
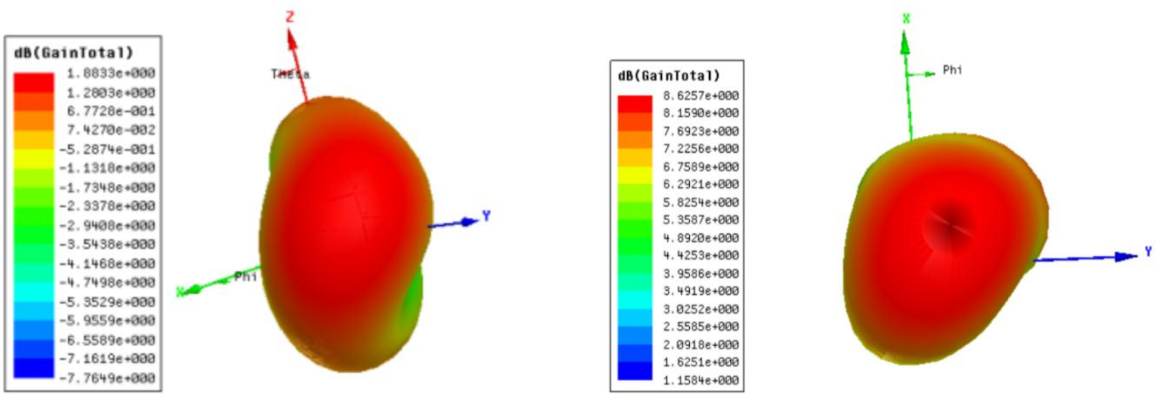


Figure III.24: Result of the *S*-parameters of Iteration 2 for different values of D.

Figure III.25 shows the 2D radiation pattern and 3D gains of different resonator distances:



(a)



D= 1mm D= 2mm

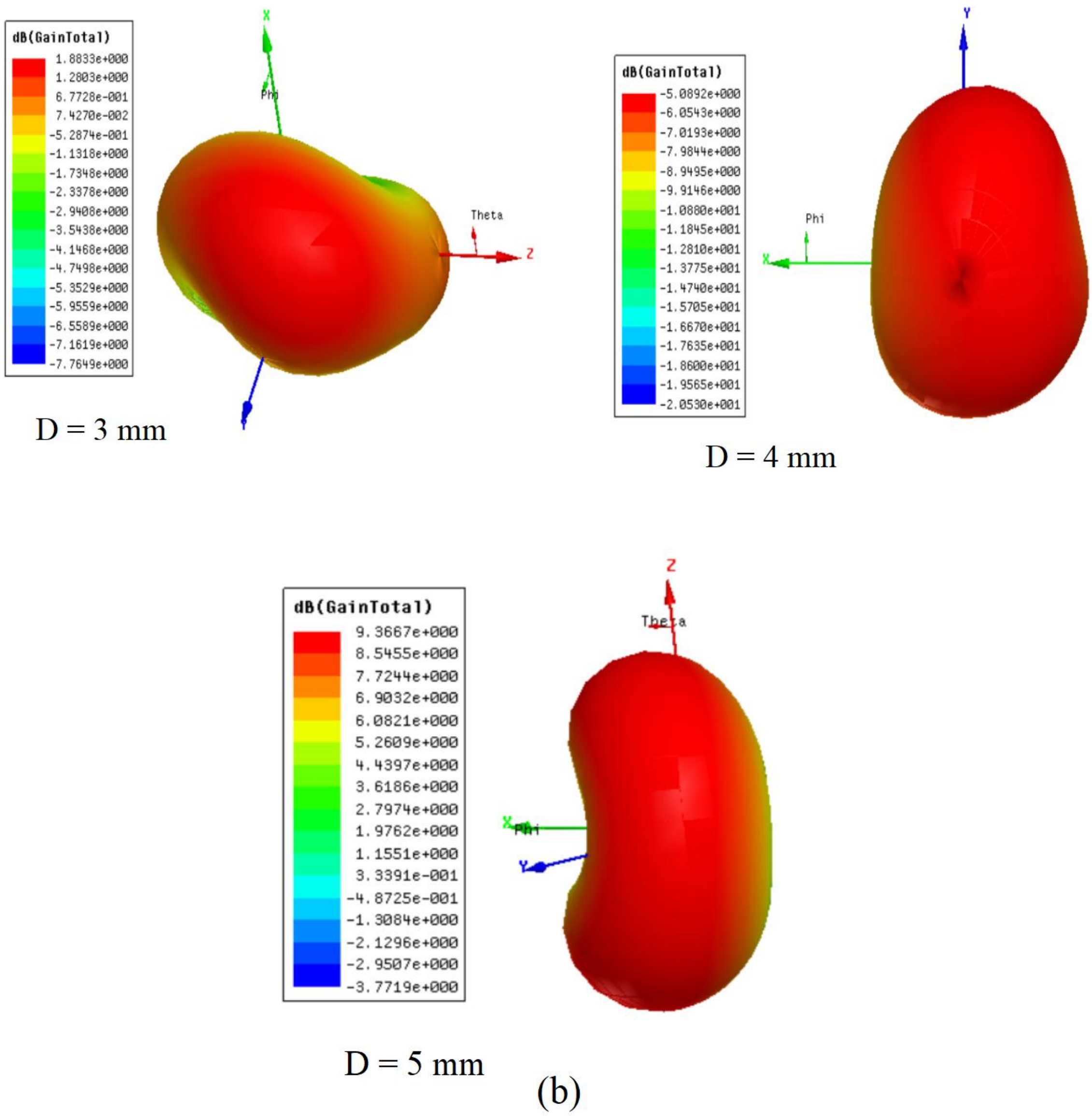


Figure III.25: Simulated performances of antennas for several distances: (a) the E-H plane of the radiation pattern; (b) 3D gain with a various value of D.

Subsequent to this study, we noted a considerable variation in antenna gain relative to the distance analyzed. However, through optimization techniques, we identified that the most favorable configuration occurred with a spacing of **1.7 mm** between the resonators. Despite the relatively minor variations in performance across different configurations, there was a minor difference for S_{11}, fine-tuning the spacing to **1.7 mm** resulted in noticeable improvements in key parameters such as gain, bandwidth, and impedance matching. This optimized design not only maximized the antenna's performance but also ensured efficient utilization of resources, demonstrating the importance of meticulous optimization in antenna design. The results depicting the favorable S_{11}, 2D radiation pattern, and 3D gain are showcased in Figure III.26 and Figure III.27:

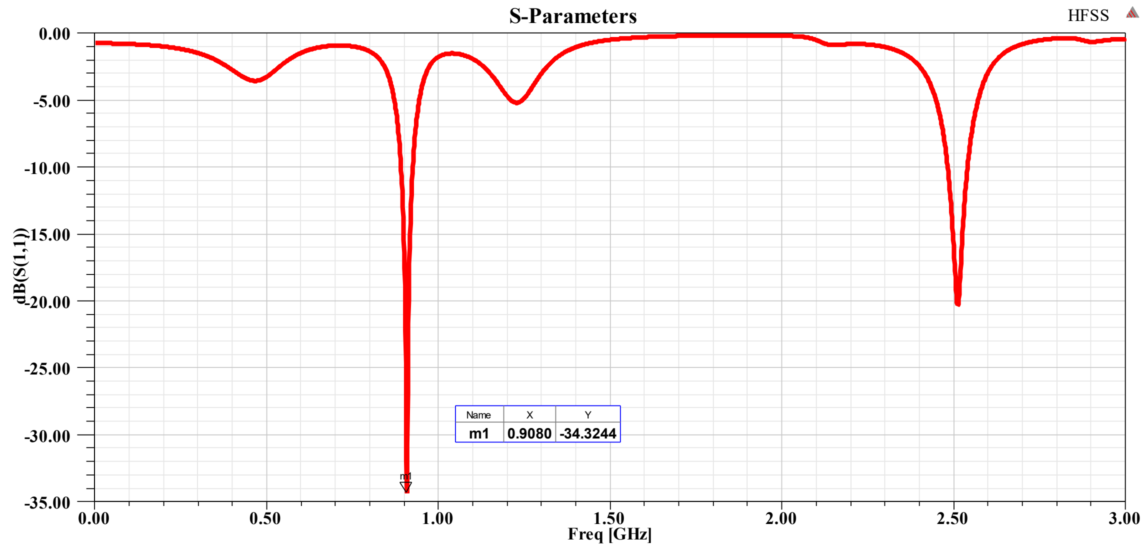


Figure III.26: S_{11} parameters result for a distance of 1.7 millimeters.

The optimization process ensures that the gain for this distance is superior compared to other configurations of Figure III.27.

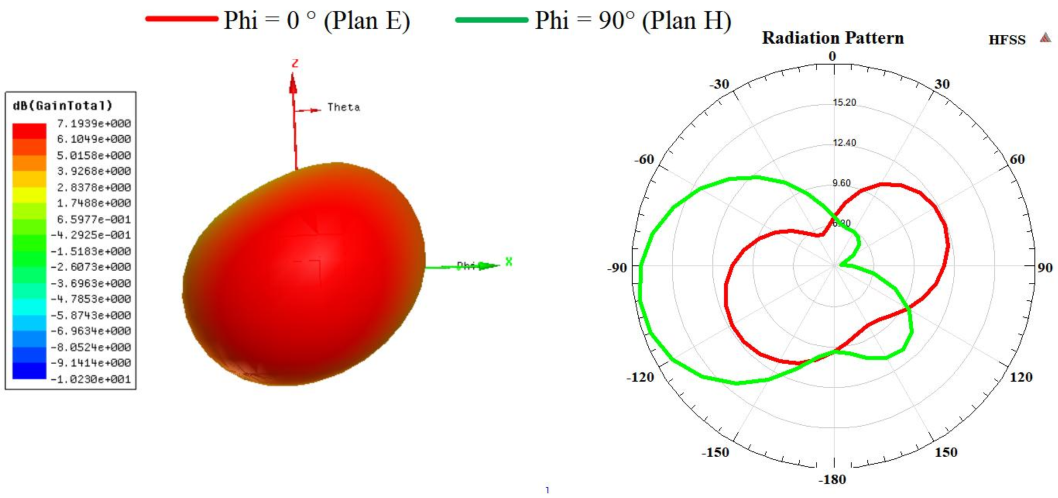


Figure III.27: The Coordinated 3D Gain and the E and H plane Radiation Pattern of iteration 2 (D =1.7 mm).

c) Antennas with five CRHCRs "Iteration 3":

This iteration includes five resonators etched into the ground. The simulated reflection coefficient of the proposed antenna is incorporated in Figure III.28.

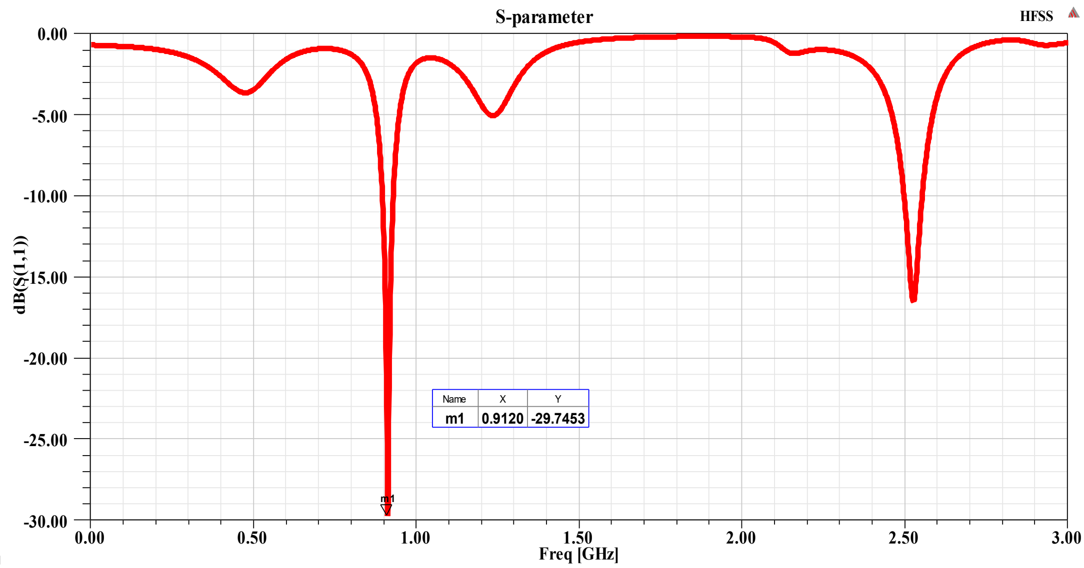


Figure III.28: The simulated return loss of the antenna loaded with five CRHCR.

These results show that the S_{11} achieves a value of -29.7 dB at 0.912 GHz and a bandwidth around 38 MHz. This antenna operates in two bands, offering an additional frequency range around 2.5 GHz. Figure III.29 depicts the 3D gain and 2D radiation pattern obtained using HFSS.

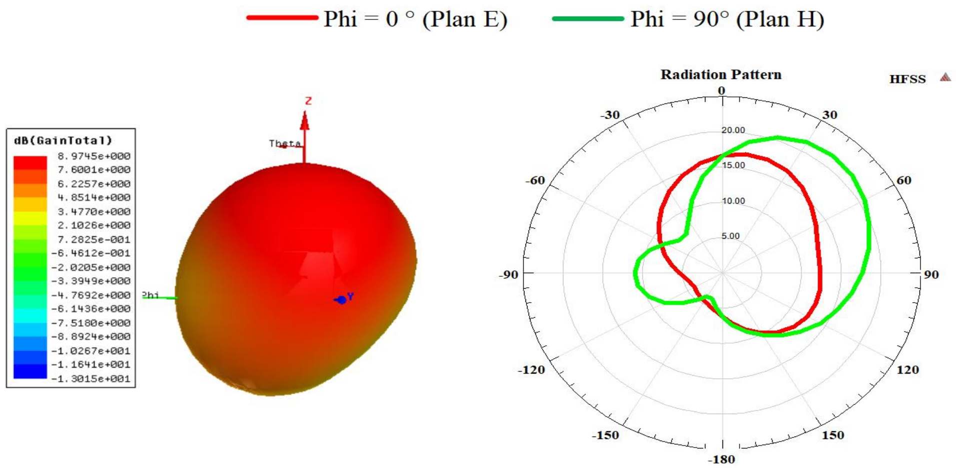


Figure III.29: Simulated gain and radiation pattern of iteration 3 at 0.912 GHz.

d)-Antennas with nine CRHCRs "Iteration 4":

In this iteration, nine resonators are incorporated into the ground. Figure III.30 displays the S_{11} results.

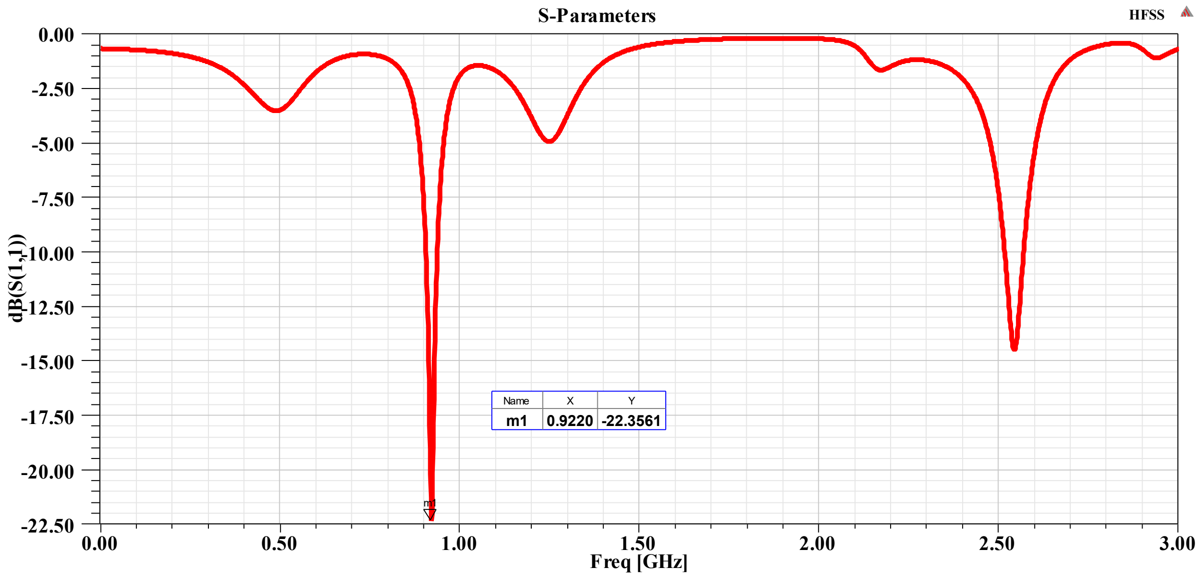


Figure III.30: The simulated return of the antenna loaded with nine CRHCR.

The radiating patterns of the antenna in the E and H planes and 3D gain are shown in Figures III.31.

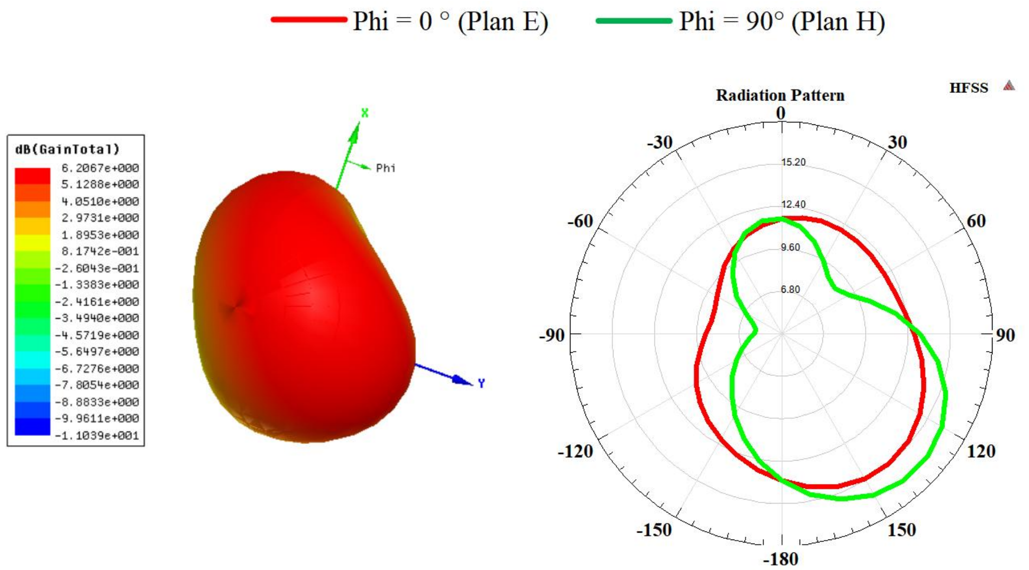


Figure III.31: The E-H radiation pattern of iteration 4 at 0.922 GHz.

We observe that the antenna exhibits a return loss of -22.35 dB and a bandwidth of 33 MHz at 0.922 GHz, achieving a maximum gain of 6.20 dBi

e) Antennas with many CRHCRs "Iteration 5":

In this step, we will fill the entire partial ground with these resonators, as illustrated in Figure III.32.

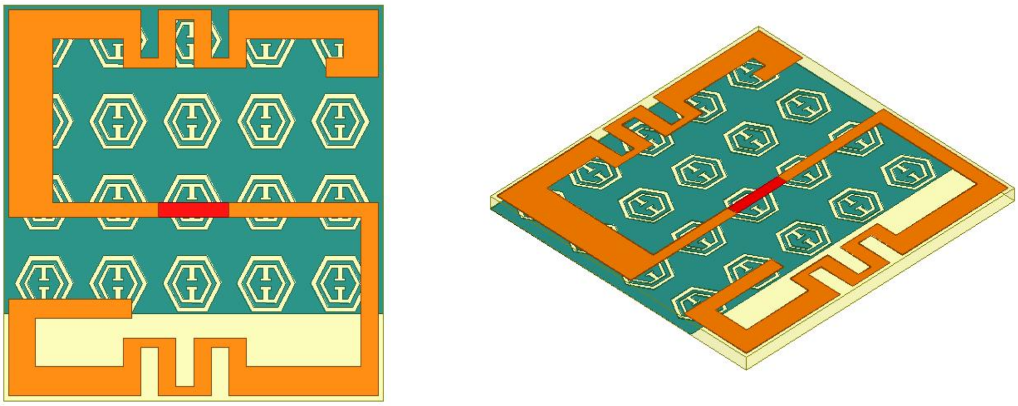


Figure III.32: Structure with many CRHCRs (iteration 5).

The simulation results of return loss, as depicted in Figure III.33, illustrate a degradation in the S11 of the antenna around 0.9 GHz, while a microwave band, commonly utilized in RFID technology, emerged around 2.45 GHz.

The value of S_{11} at this frequency is less than -25 dB and the dimensions of the proposed antenna are 43 x 41 x 1.6 mm³

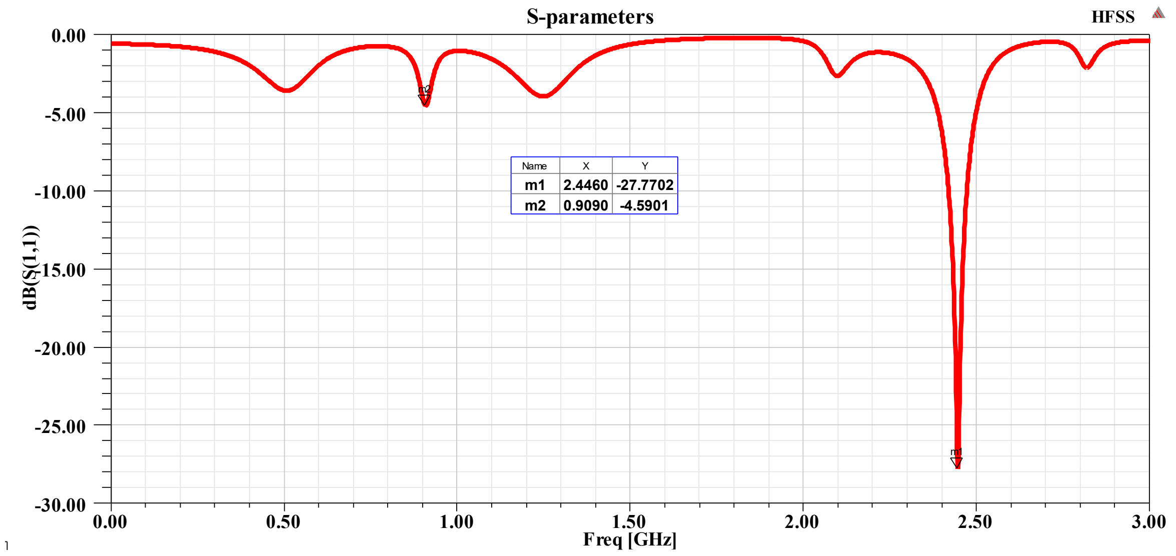


Figure III.33: S_{11} coefficient results of iteration 5.

At 2.45 GHz frequency, radiation patterns and gain are depicted in Figure III.34.

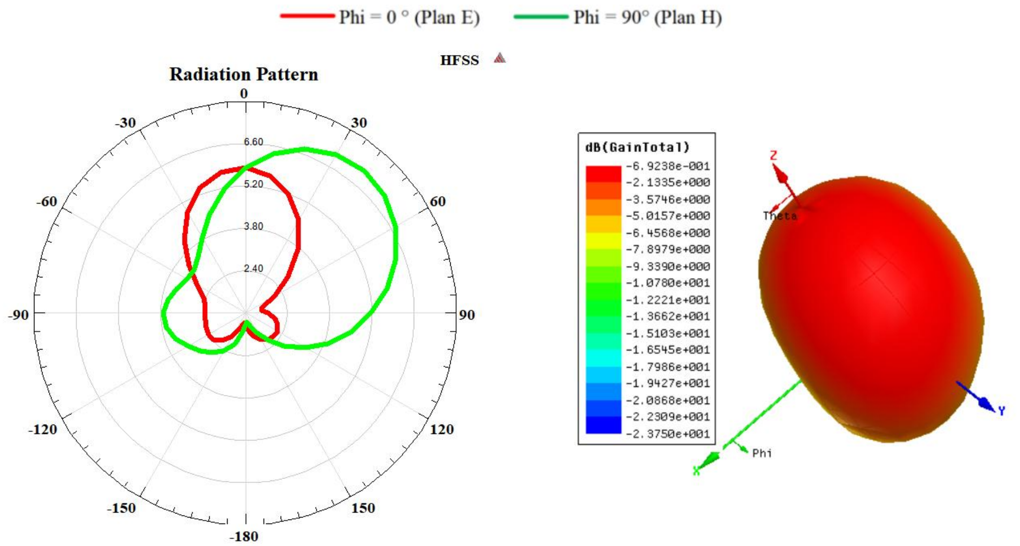


Figure III.34: 3D gain and 2D diagrams of iteration 5 at 2.45 GHz.

We note that further optimization is needed for this antenna to enhance both the S_{11} and gain.

To sum up, the simulation results of S_{11} for all iterations are shown in the following Figure.

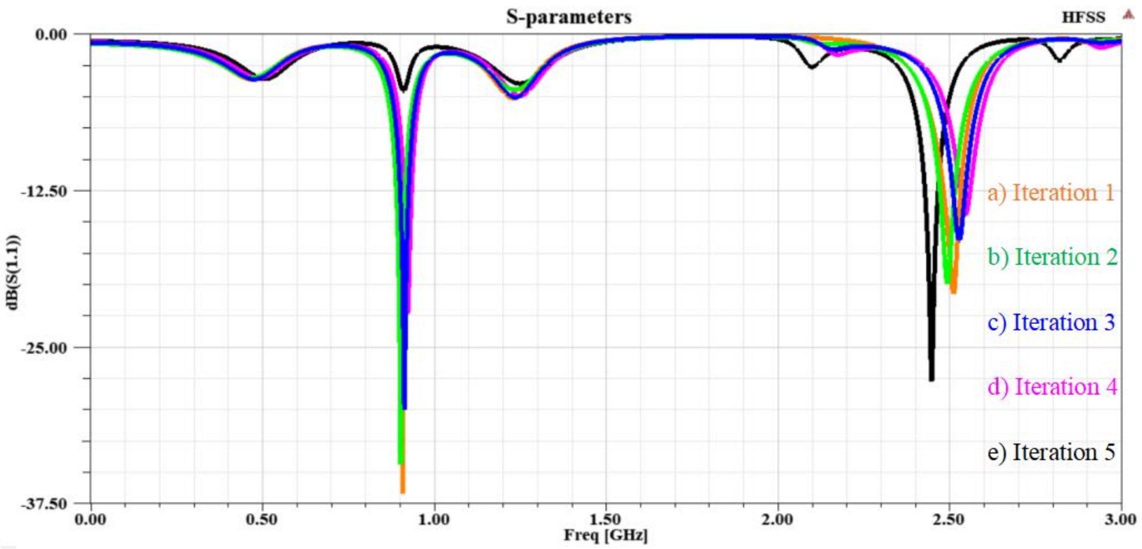


Figure III.35: Reflection coefficients of the proposal antenna with different iterations.

We selected iterations three and five resonators due to its promising results.

The simulation results proved that it is possible to reduce the size of the proposal RFID antenna by increasing the number of metamaterial resonators (Figure III.36).

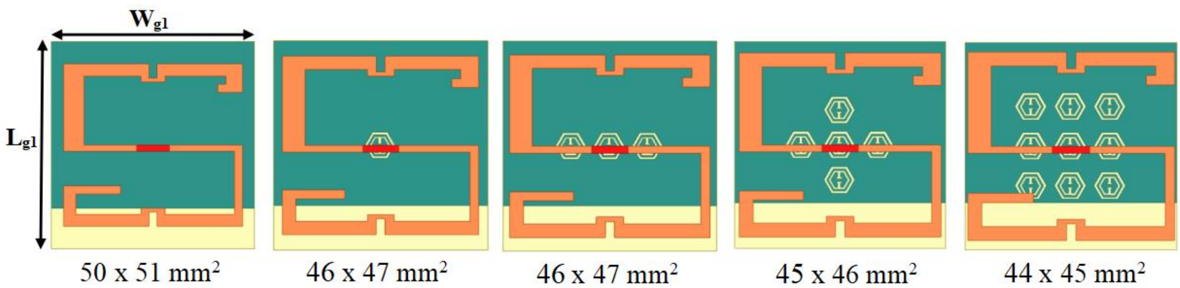


Figure III.36: The various iterations of the MTM design and its miniaturization.

III.5.3 MTM Antenna design loaded CRHCRs resonators in top:

For the continuity of this work, we will simulate the folded asymmetric meander-line antenna, using only two resonators on the top face and removing all resonators from the bottom face, as shown in Figure III.37.

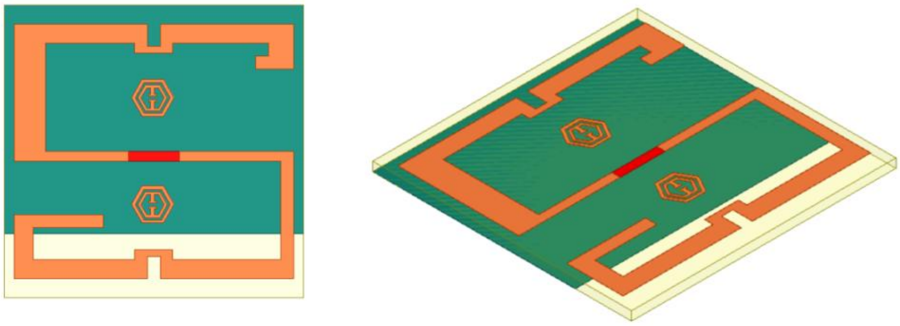
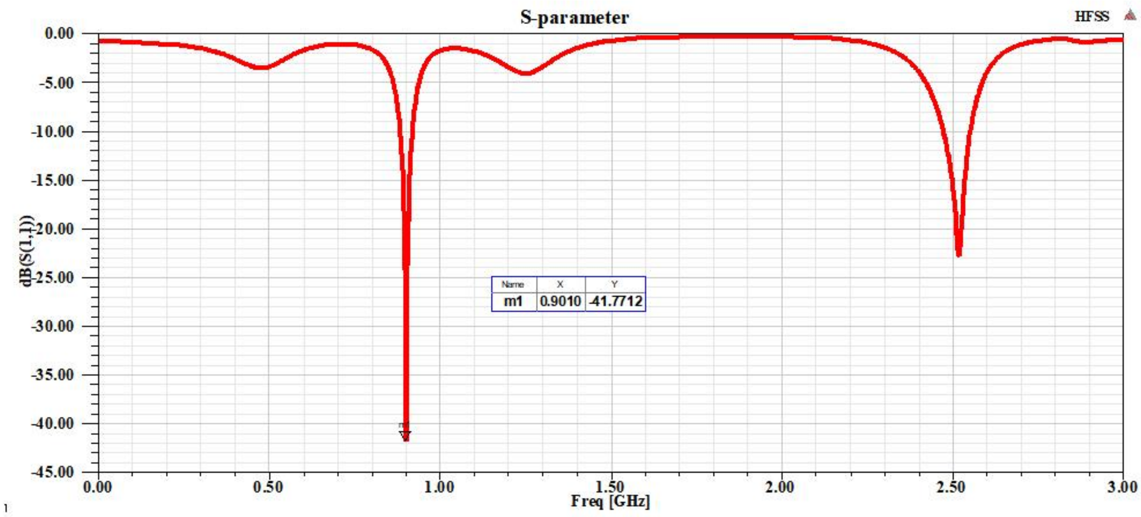
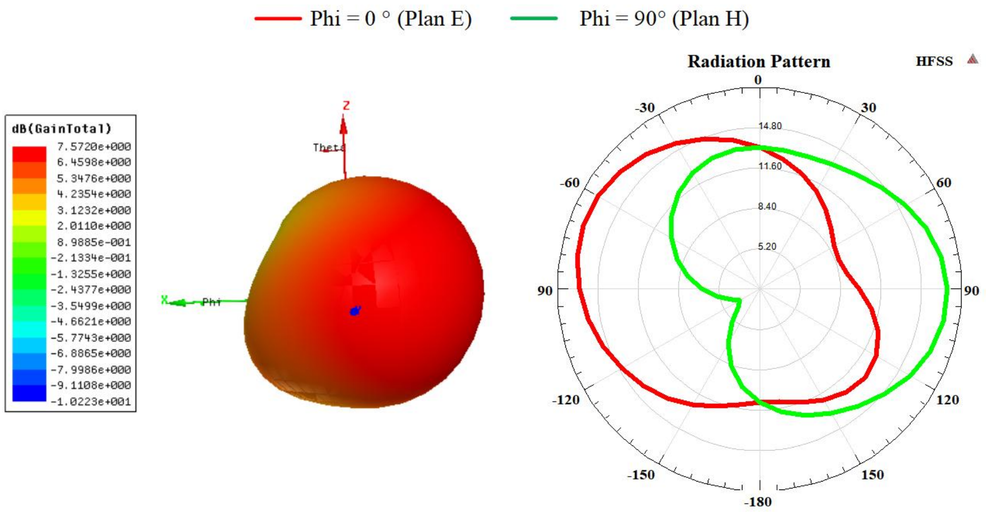


Figure III.37: Structure of the S-shaped folded meander-line antenna with MTM on the top face.

The simulation of this topology produces the results shown below, which include the S_{11}, gain, and radiation pattern.



(a)



(b)

Figure III.38: (a) Parameter S_{11}, (b) Radiation pattern within the E-H plane, and 3D gain at 0.901 GHz.

III.5.4 MTM Antenna design loaded CRHCRs resonators in top and bottom:

Next, we attempted to incorporate the same type of resonators inside the radiating element of the chosen antenna (iteration 3: five resonators), as illustrated in Figure III.39. Beginning with two resonators, we evaluated their impact on key parameters such as gain, directivity, and bandwidth. These resonators were carefully placed on the substrate to optimize their interaction with the main antenna and contribute to enhancing its performance.

This systematic approach provided valuable for refining the antenna design further and maximizing its performance.

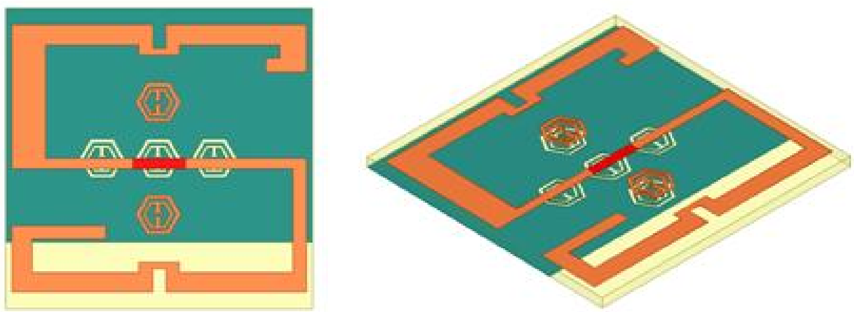


Figure III.39: Proposed antenna with CRHCRs resonators in top and bottom.

The following Figures show the S_{11} parameter, the radiation pattern in the E-H plane, and the

3D gain values.

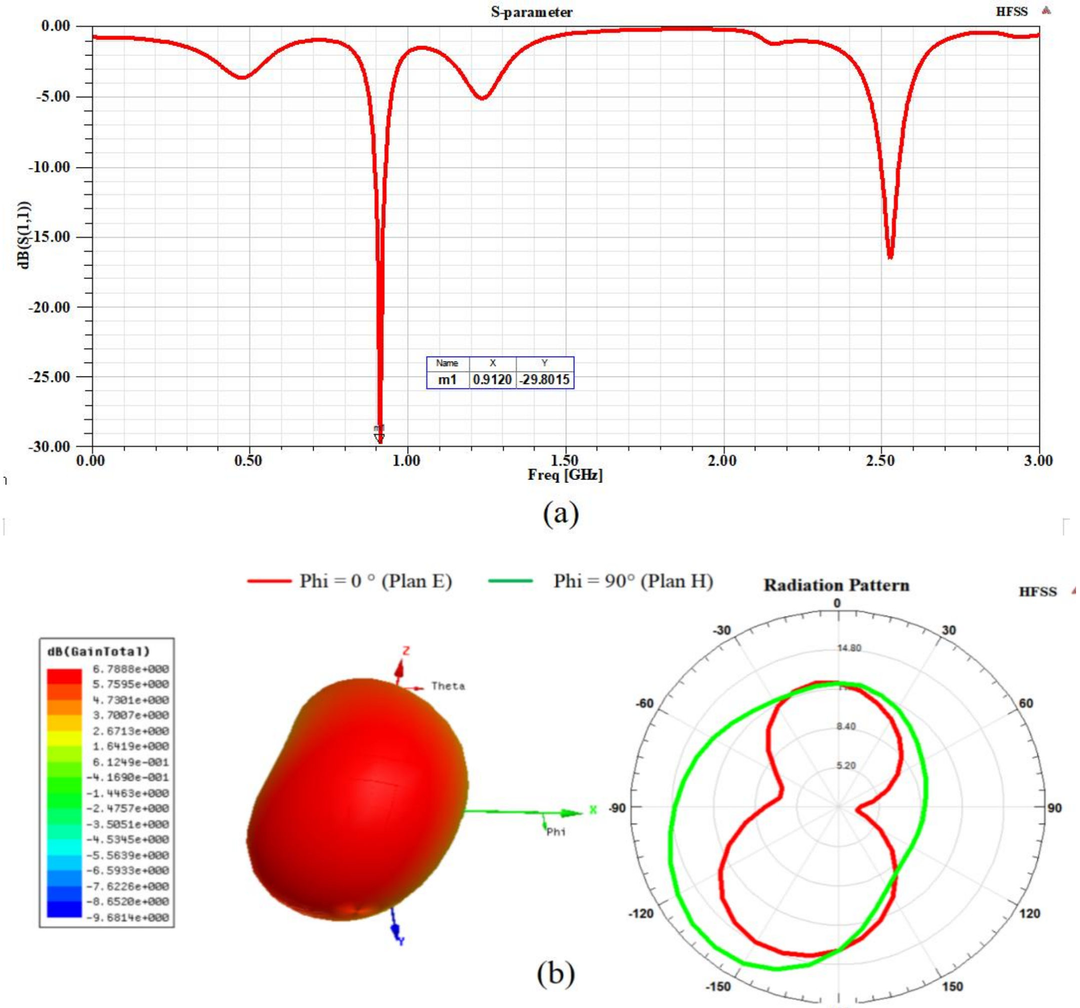


Figure III.40: The simulation results of proposed antenna, (a) Parameter S_{11}, (b) radiation pattern in the E-H plane and 3D gain at 0.912 GHz.

In the following Figure, we have added two resonators to the antenna structure and changed their positions to enhance performance. These adjustments help achieve better efficiency and more precise adaptation to the specific requirements of the RFID application.

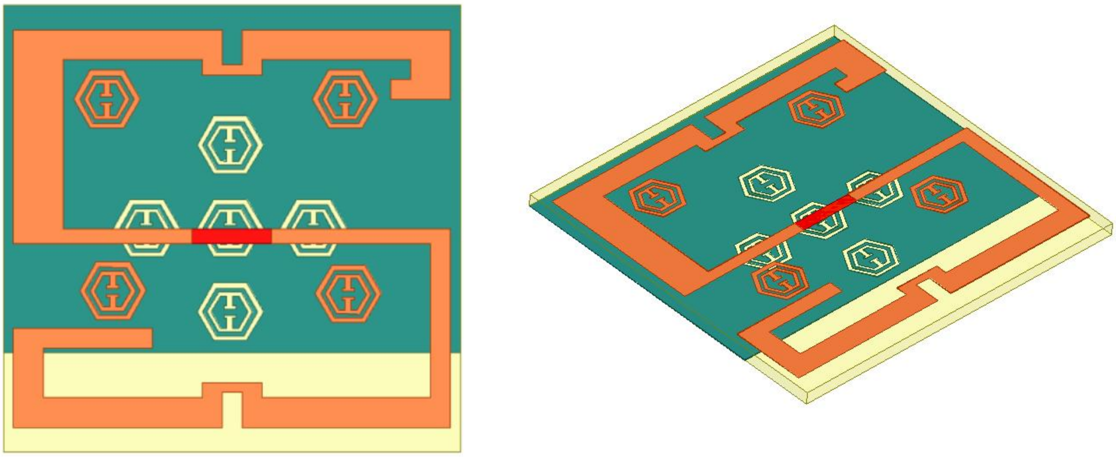


Figure III.41: Structure with four CRHCRs in top.

Figures (III.42 and III.43) illustrate the S_{11}, radiation pattern, and gain of the proposed antenna, with resonators positioned on the upper face within the radiating element. These results are obtained for a size of 46 x 45 mm² (Figure III.41),demonstrating an adaptation of -33 dB, a bandwidth of about 33 MHz, and a maximum gain of 7 dBi.

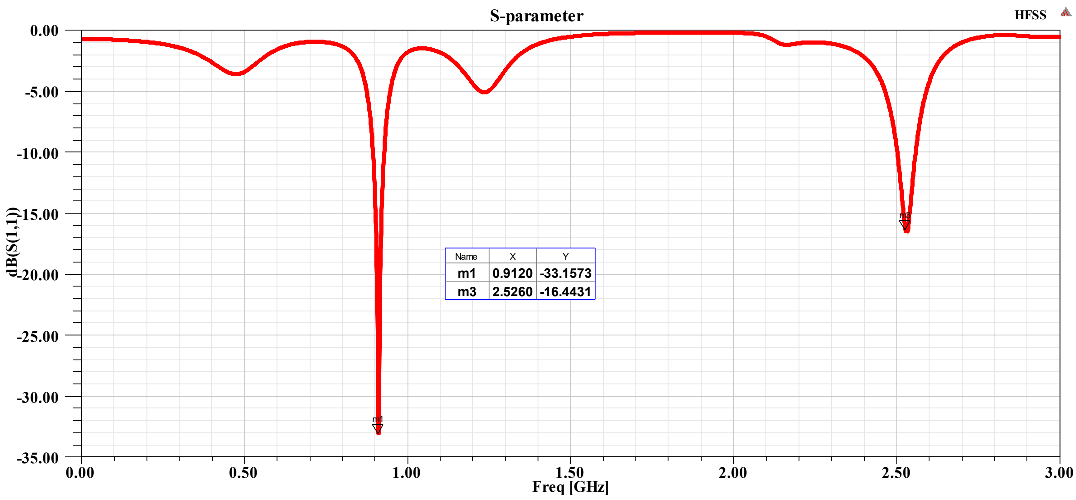


Figure III.42: The S_{11} parameter for antennas with resonators located at the top and bottom.

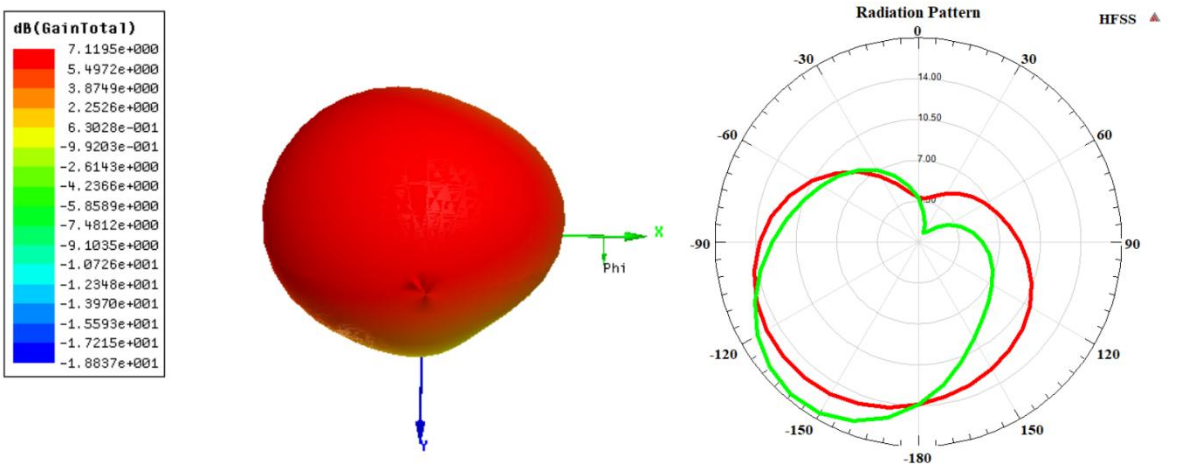


Figure III.43: Radiation pattern and gain for the proposed antenna at 0.912 GHz.

III.5.5 MTM Antenna design loaded CRHCRs in bottom and RHCRs in top with two lines:

To advance this study, we have incorporated two additional lines into the S-shape folded meander-line antenna to enhance its flexibility and adaptability, as depicted in Figure III.44 By using lines, antenna achieved optimum performance.

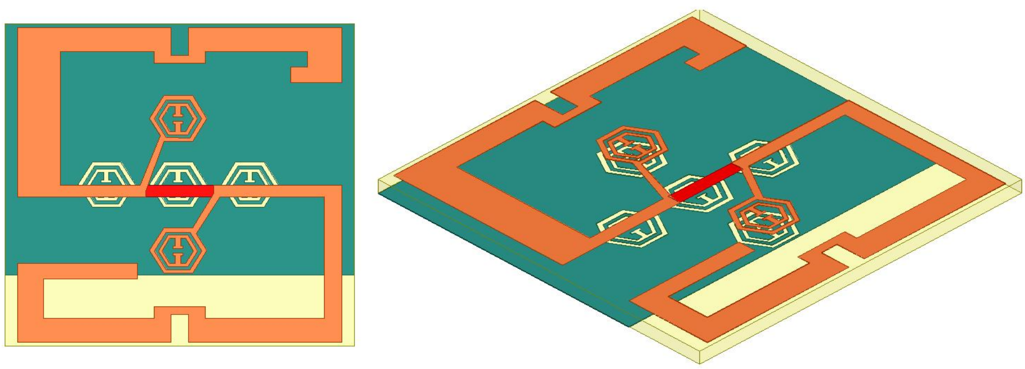


Figure III.44 : Topology of proposed antenna with two lines connected with RHCRs in top layer

This technique yielded remarkable results, significantly enhancing the gain value by 4.4 dB and reducing S_{11} to approximately -43 dB at the operating frequency of 0.915 MHz, as illustrated in Figure III.45

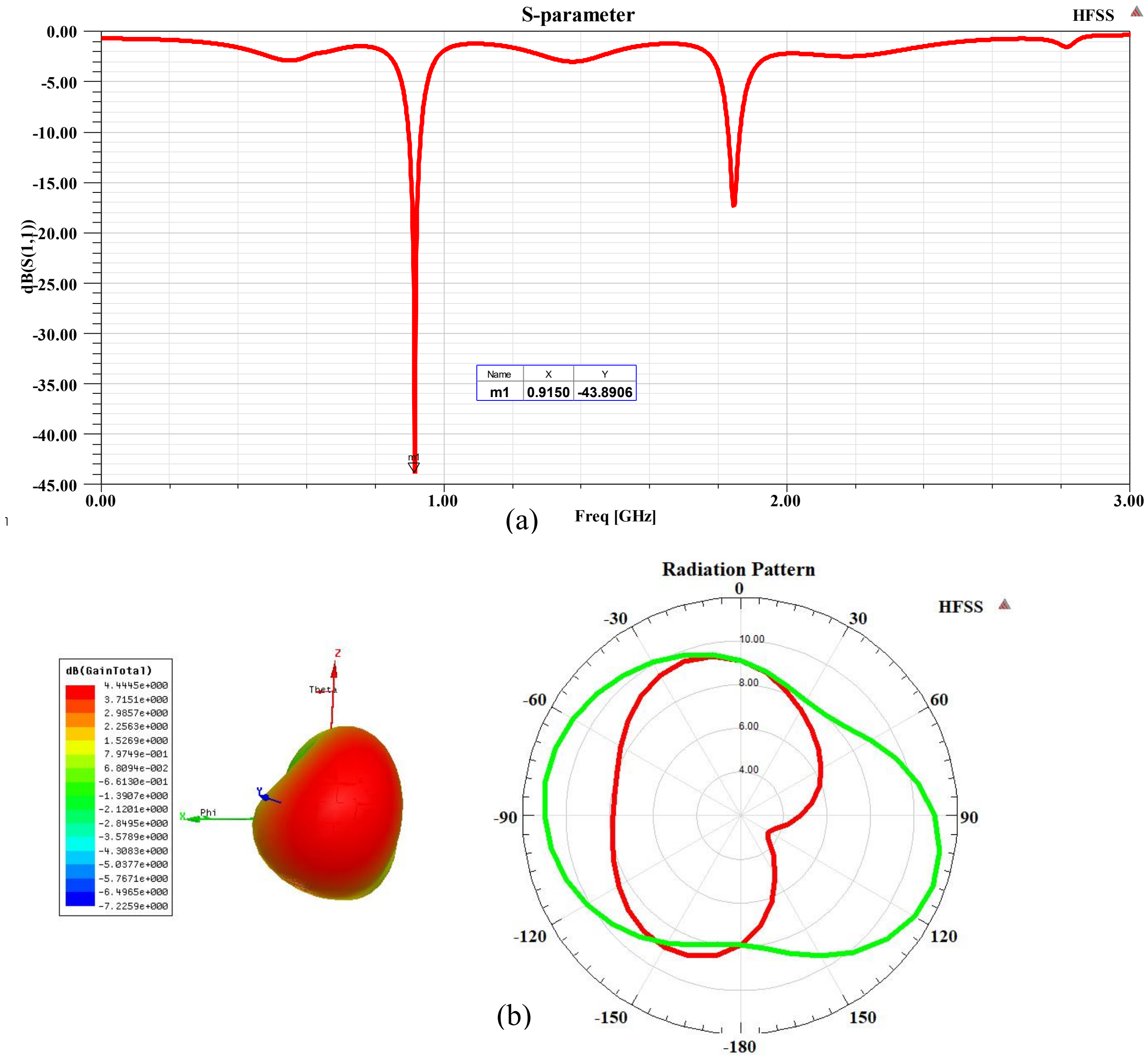
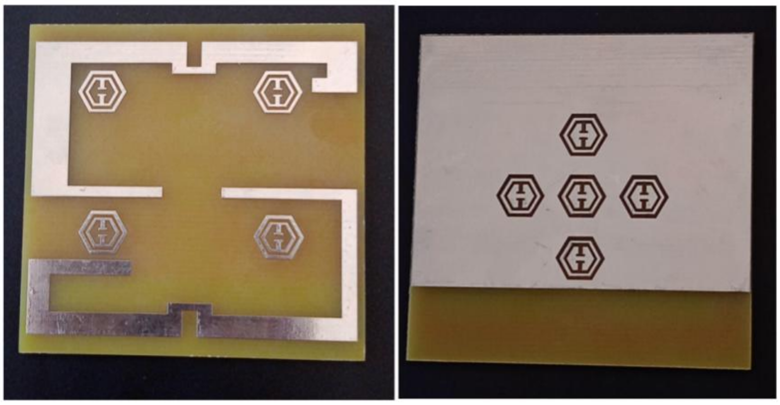


Figure III.45 : (a) The S_{11} parameter, (b) radiation patterns and antenna gains obtained with HFSS software at 0.915 GHz.

III.6 Experimental Results:

After optimizing the parameters of the proposed antennas, we opted for the structure depicted in Figure III.41 as our prototype for manufacturing. To ensure precise and efficient fabrication, we rely on Gerber files to convey the necessary data for antenna production. These files contain detailed information about layers.

The prototype has been fabricated by using LPKF machine. Figures III.46 and III.47 illustrate the manufactured prototype. As can be seen in the Figure, the structure of this antenna is relatively simple as it can be fabricated on a single layer. The fabricated antenna has an area of 46 mm x 45 mm and an SMA connector will be soldered in the middle of the antenna, to use as a feed port.



(a) (b)

Figure III.46: Manufactured antenna, (a) Prototype top view, (b) Prototype bottom view.

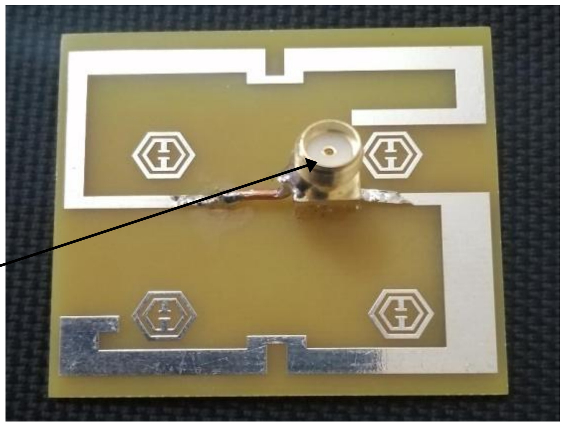


Figure III.47: Connecting the SMA connector to the antenna feed point

The measured result is performed by using Rohde & Schwarz Vector Network Analyzer ZNB. Figure III.49 reports the results of the reflection coefficient obtained from the measurement.

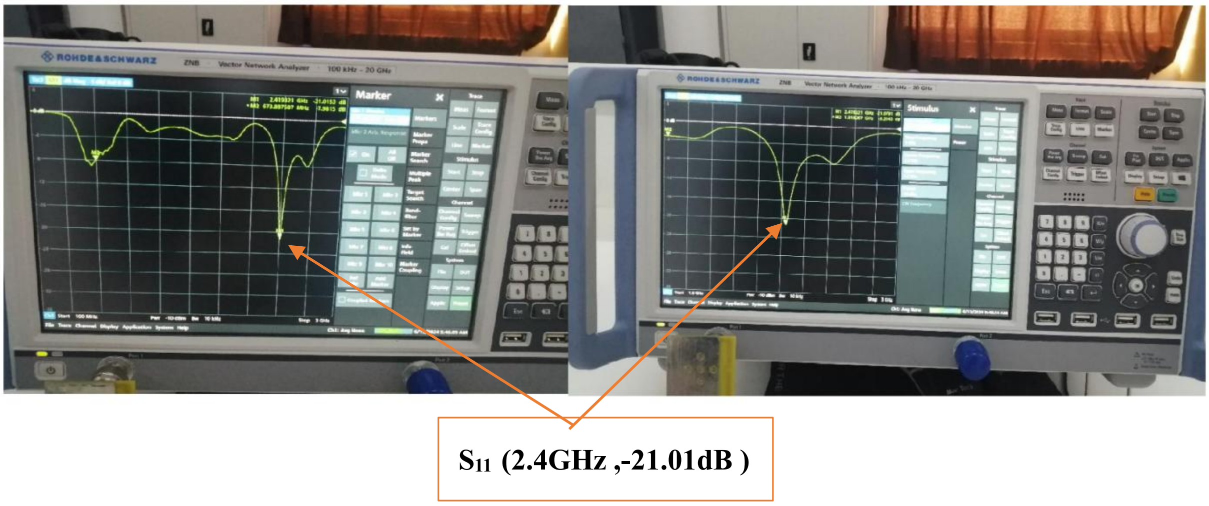


Figure III.48. Measurement of the reflection coefficient against frequency using Network analyzer ZNB.

From the comparison between the numerical and the measured results, we can observe that there is a relative agreement between them. The slight difference between the numerical results and measurement is due to the fabrication error, the SMA connector and uncertainty in substrate thickness and dielectric constant.

The measurement results indicate the second peak an adaptation of -21 dB at the frequency around 2.4 GHz (Figure III.48).

Another method to validate our results is the comparison of our simulated results with some published works in the literature (Table III.4).

III.7 Comparative analysis:

A comparative analysis between the designed antennas to literature has been presented in Table III.4, in terms of the size, frequency, S-parameters, gain, and substrates.

Ref	Size (mm^3)	Substrate	Frequency (GHz)	S_{11} (dB)	Gain (dB)
[8]	$38 \times 45 \times 1.6$	Fr4 ($\varepsilon = 4.4$)	2.4 5.8	-20 -34	2 3.5
[9]	$80 \times 80 \times 4.572$	Fr4 ($\varepsilon = 4.4$)	0.910	-24	3.07
[10]	$75 \times 25 \times 1.6$	FR4($\varepsilon = 4.4$)	0.867	-44.15	1.5
[11]	$20 \times 18 \times 1.6$	FR4($\varepsilon = 4.4$)	0.900	-23	1.8
[12]	$30 \times 30 \times 1.6$	Fr4 ($\varepsilon = 4.4$)	0.900	-22	0.18
[13]	$131.1 \times 34 \times 0.49$	Fr4 ($\varepsilon = 4.4$)	0.915 2.45 5.8	-28 -27 -16.5	1.8 7 7
Proposed antenna	46×45×1.6	Fr4 ($\varepsilon = 4.4$)	0.912	-33	7.11

From this table, the proposed antenna demonstrates acceptable values in term of dimensions and S_{11}, and exhibits the best performance in terms of gain.

Conclusion:

A novel design of compact antenna working around 915 MHz based on metamaterials for RFID applications is presented in this chapter. This proposed miniaturized RFID antenna inserted a complementary double-rings hexagonal closed resonators loaded dumbbell-shaped resonator (CRHCRs) into the partial ground.

Design and simulation of these antennas was done using HFSS. The smallest proposed antenna in these designs measures 44x 45 x 1.6 mm^3

Additionally, the designed antenna exhibits favorable radiation characteristics. The simulation results proved that it is possible to reduce the size of the RFID antenna by using folded shapes and metamaterial techniques. The selected antenna for manufacturing exhibits the following simulation performances: an S_{11} value of -33 dB at a frequency of 0.912 GHz, and a bandwidth for |S-parameters| less than -10 dB of approximately 38 MHz. The fabricated antenna occupies an area of 46 mm x 45 mm.

Numerical results were validated against measurement results and other research findings; the comparison of results shows good agreement.

Bibliography of chapter 3

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General Conclusion

General Conclusion

This work is enclosed in the context of RFID antenna design working at the UHF (800-960 MHz) frequency band as well as understanding the procedures and problems of the design process.

The popularity of the UHF band have shown that optimization techniques will be of great interest in the various RFID applications from access control to supply chain, such as auto-theft protection, merchandise tracking, collecting tolls without stopping, access control of people into buildings, dispensing goods, access to ski lifts, etc.

Passive RFID systems that operate in the UHF band generally suffer from limitations related to big size and low performance of antenna. These are the main challenges when designing the UHF antenna.

This work proved that the microstrip antennas are now great candidates for the current systems because of their low profile, light weight, and ease of fabrication. However, these antennas have some limitations, such as a low gain and a very narrow band passing through. The use of the meander line and metamaterials in the design of microstrip antennas seems to be an effective and innovative solution that overcomes their disadvantages and makes them compact and efficient.

Antenna's radiation properties are also important for the UHF band since this band is affected more than the HF or lower bands by environmental interference (i.e. metals, liquids, human body absorption). This necessitates the designer to improve antenna radiation characteristics such as radiation pattern, return loss and gain.

The research work developed during this dissertation focused on the design, simulation and realization of UHF RFID antennas, the main performances of these RFID-UHF antennas were evaluated using HFSS electromagnetic simulation software.

The contents of this work have been divided into three chapters (excluding the conclusions and future work), as follows, after, presenting the general concepts and theory about technology, in chapter I.

An overview of antenna parameters has been reported in the first part of chapter II. The rest of the chapter has been dedicated at providing a state of the art of RFID miniaturized antenna design. Various methods for reducing antenna size: fractal geometries, folded dipoles... To date, the folded antenna configuration remains the most effective in terms of size reduction.

Finally, in chapter III, we discussed all of the proposed RFID antennas. The research work developed during this chapter focused on the design and simulation of UHF RFID antennas, using HFSS software. In this chapter, there are various stages of design and simulation, where we explore multiple options to optimize the performance of our RFID antennas.

Initially, we simulated a single ring antenna with a large size. While the results obtained were acceptable, we soon recognized the significant potential for improvement by modifying the antenna geometry and applying miniaturization techniques. Subsequently, we observed a clear improvement in performance.

Following our extensive research, we identified partial grounding as a promising solution to further enhance the performance of our antenna. Next, we designed a complementary hexagonal-shaped metamaterial (MTM) resonator (DGS-CRHCR) with negative permeability. After integrating this complementary resonator into a proposed antenna (S-shaped folded meander line), we proceeded to evaluate and compare performances. Additionally, we applied the resonator to a substrate, which further enhanced the antenna's performance.

Through multiple design iterations, our goal was to achieve optimal results, leading to a significant enhancement in antenna performance in terms of return loss, directivity, and gain.

We can conclude that the use of folded and DGS-metamaterials techniques in different configurations have improved high performance of patch antennas in terms of miniaturization, matching, gain and radiation efficiency.

For some of our antenna designs, we have achieved high gains up to 7.11 dBi and reflection coefficients more than –30 dB.

The simulated results of RFID with four complementary resonators MTMs etched in ground and four resonators MTMs etched on substrate were successfully validated with measurements. More generally, several promising research areas are currently emerging and paving the way for advancements in RFID antenna design:

- Designing RFID antennas whose input and radiation properties remain nearly unchanged when the transponder is attached to different substrates, such as paper, wood, metal, or living tissues.
- Developing RFID antennas that operate with UWB (ultra-wideband), dual-band UHF, and microwave bands.
- Utilizing artificial intelligence for optimizing RFID antenna designs.
- Designing multi-antenna tags.

RFID technology is expected to become ubiquitous in the future; therefore, future research axes may greatly benefit from its advancements.

Annex

Annex

Implementation of the Arduino RC522 RFID module to read/write IDs on tags

I -Presentation:

Today, RFID (Radio Frequency Identification) technology is utilized across a myriad of applications, including access control, supply chain management, retail, healthcare, and transportation. It provides a practical way to locate, identify, and track items remotely without requiring close physical contact.

In this annex, we will present the development tools used in our application, including their installation and configuration. Following this, we implemented and developed an application based on the RFID kit that allows for the identification and modification of tag identifiers.

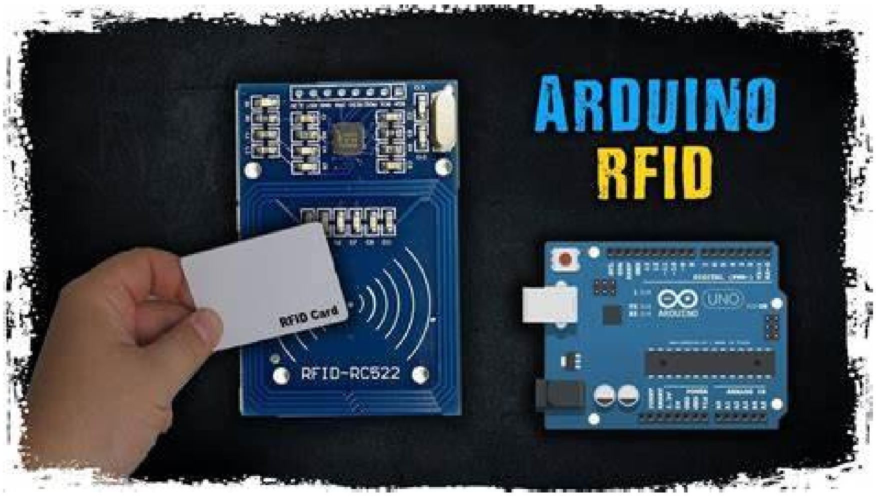


Figure 1: RFID Reader with arduino.

I.1 Electronic Tools :

We will use a variety of electronic equipment to carry out our project because of its affordability, effectiveness, simplicity, and low cost. Below are the project's constituent elements and how they work:

- Computer
- USB cable to connect the arduino card to the computer
- Reader RFID RC522.
- RFID Tag “blue key ring and card ”
- Arduino Card
- Breadboard

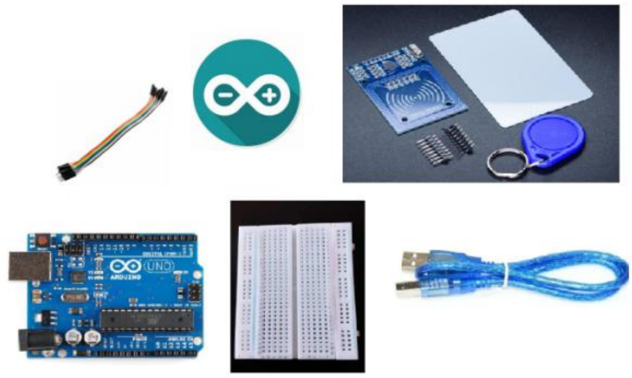


Figure 1: RFID Equipment.

I.1.1 Reader RFID RC522:

It is a bi-directional device that both sends signals to RFID tags and reads their responses. The reader, based on the MFRC522 integrated circuit, is designed to generate an electromagnetic field at 13.56 MHz for communication with the tags.

I.1.1.a - MFRC522 RFID Module Read/Write (13.56MHz):

The RC522 module offers an interface that enables contactless identification using RFID badges and keys. It is based on the Philips RC522 integrated circuit. It communicates with an Arduino using an SPI interface and the HF 13,56 MHz band. The communication range is up to 6 cm, and most NFC modules function properly at this distance, though typically within 1 cm.

The RFID/NFC mechanism is based on radio waves. This module is perfect for remote projects. Open the door after using a badge to identify each individual. It is suitable for use in any identifying project. It can be utilized for any identifying project.

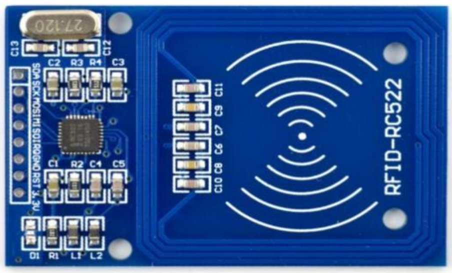


Figure 2: Reader RFID RC522

❖ RC522 RFID Reader/Writer Module Pinout:

The RC522 module has a total of 8 pins. This module supports various communication protocols and each pin has a different function for each communication protocol. The pinout of a RFID Reader module is as follows:

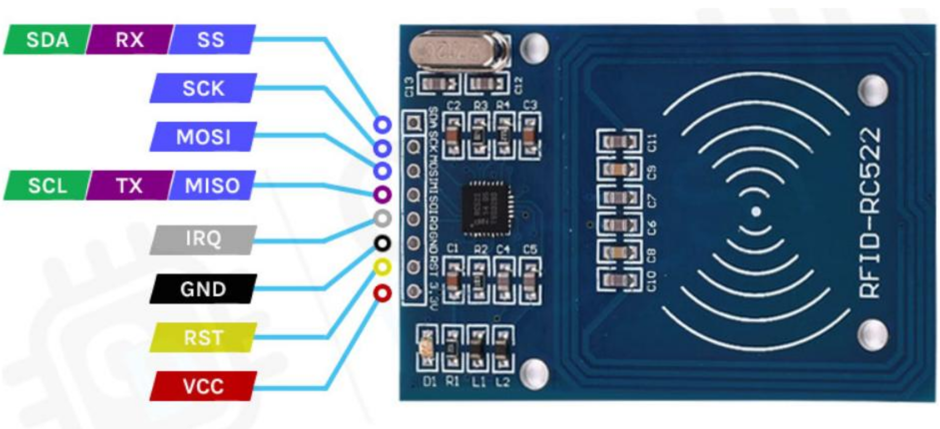


Figure 3: RC522 RFID module pins.

VCC: used to supply the module; typically, 3.3 V is used .

RST (reinitialization switch): is used to reset or re-initialize the module. The ground switch is connected to the system's mass.

IRQ, or interrupting relay: is a device that interrupts a module when a peripheral enters its range.

MISO/SCL/Tx: the MISO brooch, when used for SPI communication, acts as SCL for I2C and Tx for UART.

MOSI: master of exit and entry key for SPI communication .

SCK: series chronometer broche - used to provide a chronometer source .

SS/SDA/Rx: Act as serial entry (SS) for SPI communication, SDA for I2C communication, and Rx for UART communication.

I.2- Arduino board presentation:

The Arduino card is a platform for creatively interactive objects that is used to realize more complex electronic projects. She is made up of a physically programmable circuit known as a microcontroller and software that is used to generate and download computer codes to a mobile device.

I.2.1 Arduino Uno Card :

It's a small electronic board equipped with a microcontroller, designed to detect events via sensors and control actuators. The Arduino board thus serves as a programmable interface. The Arduino Uno model, based on an ATMega328 microcontroller clocked at 16 MHz, exemplifies this functionality.

-The ATMEL ATmega328 microcontroller: The ATMega328 is an 8-bit microcontroller from the AVR family that can be programmed in the C language.

I.2.2 Arduino board components: An labelled Arduino card is shown in the following illustration:

1- Port USB Plug a USB cable into this socket to transfer the custom control program to the Arduino.

2- The green entry/sortie pins are designed to send or receive a signal, which can take the formof a 0 volt or 5 volt tension. The ones marked with a ~ are adjustable.

3- The analog (red) inputs are meant to receive a signal consisting of 0 to 5 volts. The analog/numerical converter operates on 10 bits, or 1024 levels (including 0 and 1023 bornes).

4- The supply voltages (in violet) provided by voltage regulators are used to power an electronic circuit.

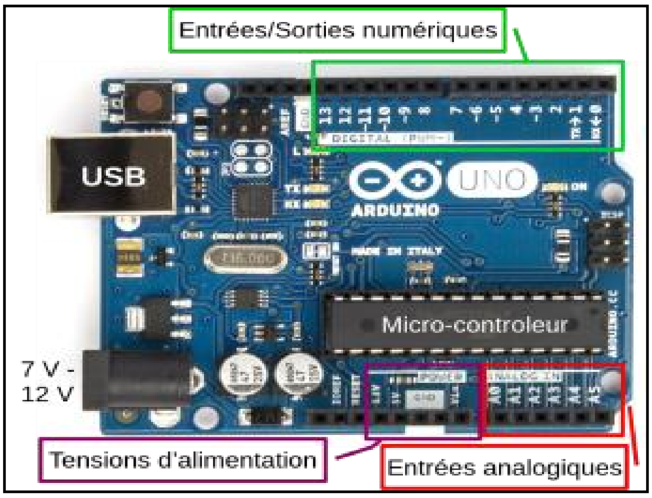


Figure 4: Description of the Arduino.

II- RFID Arduino Implementation Process:

The first step is to set up the necessary connections between the RC522 module and the Arduino board.

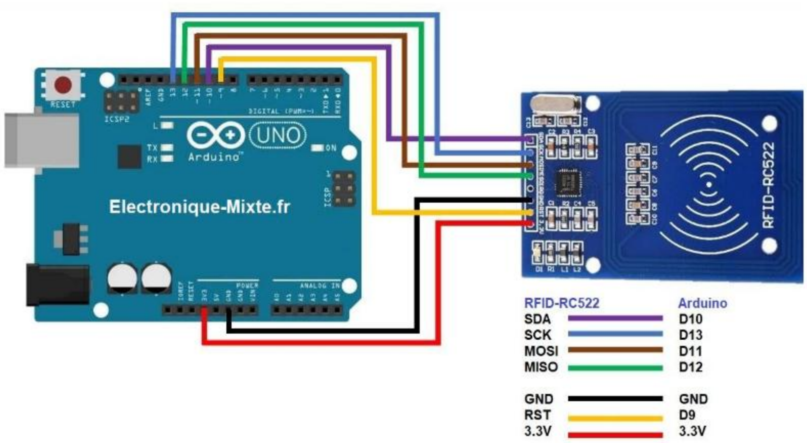


Figure 5: Connection schematic for RC522 module to Arduino Uno pins.

In the second step, we connect to the USB port of the PC and open the Arduino Uno program.

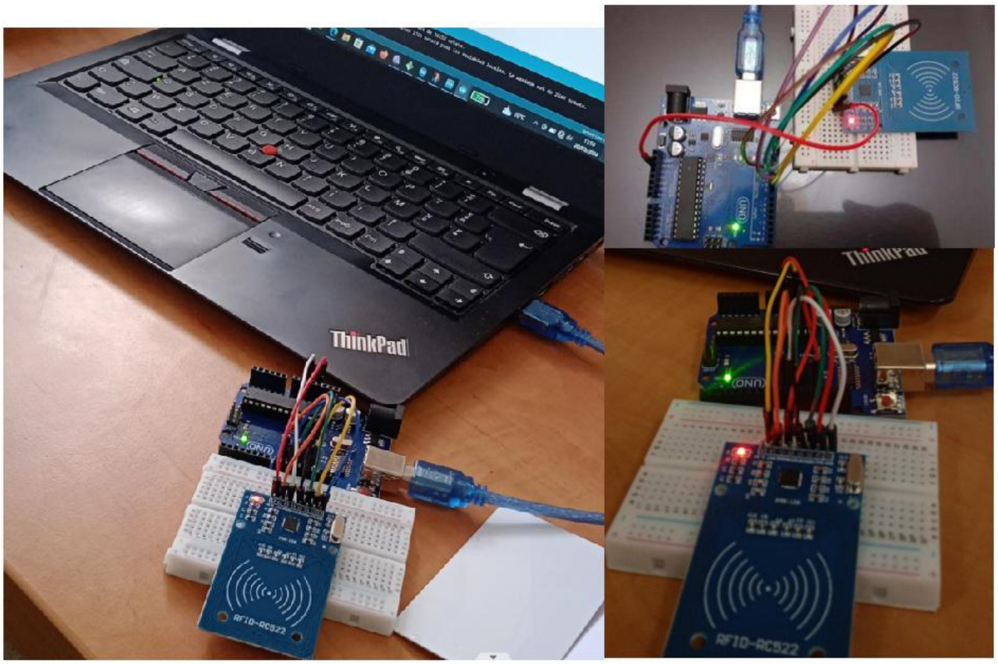


Figure 6: RFID Arduino Implementation

1- Library installation :

✓ Start program (Arduino 1.8.19).

NOTE : To use this module, the MFRC522 library must be installed:

✓ Open Arduino and go to Sketch =>Include library => Manage libraries .

2- Install MFRC522 by searching for it in the Library Manager.

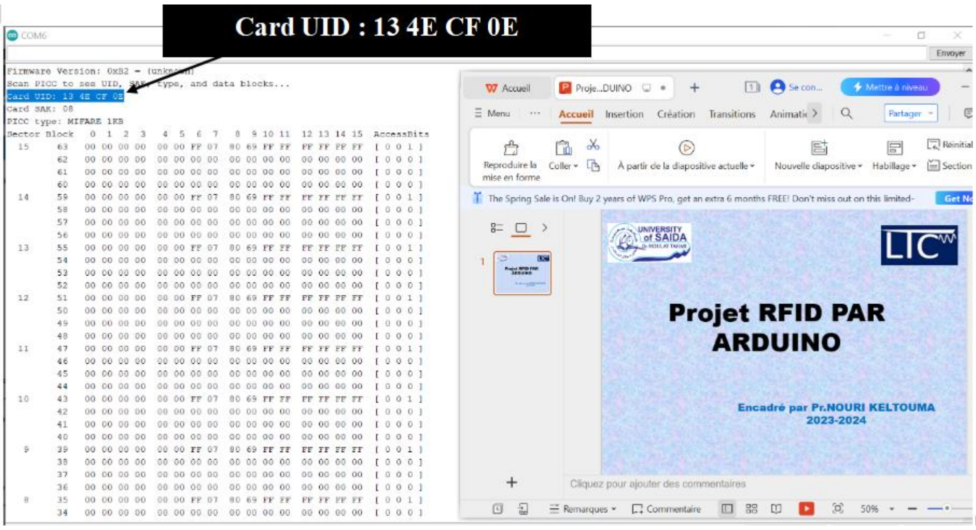
For reading RFID tag IDs : Select the scanning software in the RC522 library.

This step was utilized to use the sketch => Examples =>DumpInfo to scan the tags.

III.1 Blue key ring identifier :

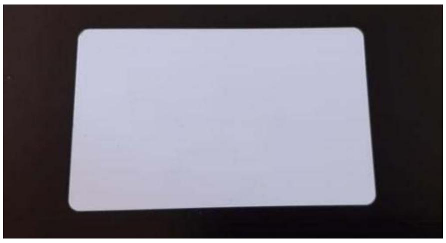
a) -Scan the Tag :

Results:

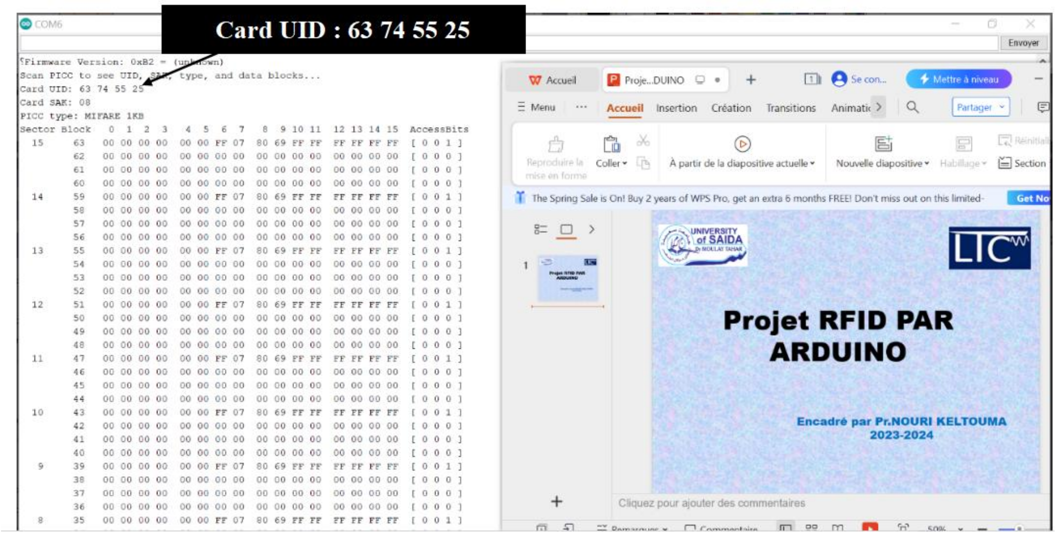


III.2 Card identification (UID)

b) **-Scan the Tag :**



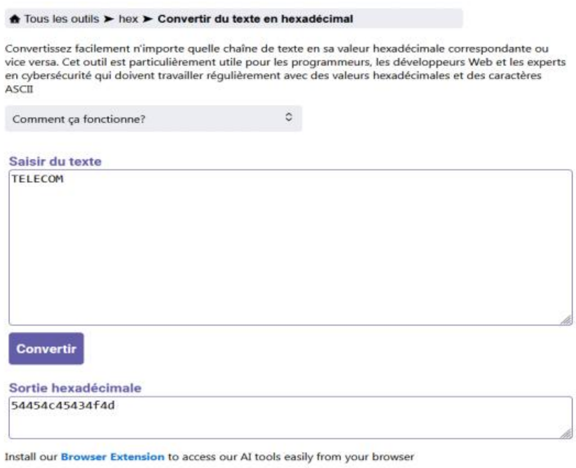
Results:

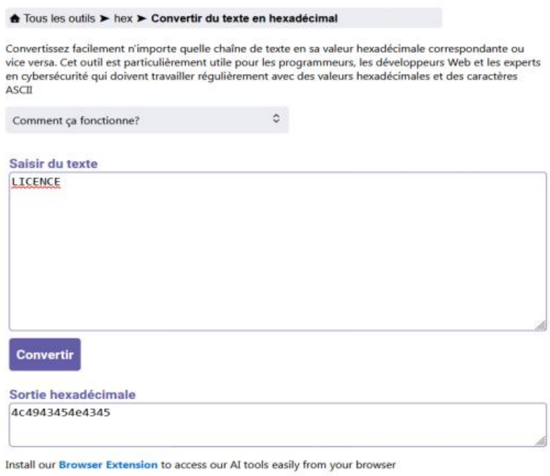


III.3 Change ID to Tag:

We have selected two text IDs, TELECOM for the white chip and LICENCE for the key ring, to replace the IDs of the two tags.

With the following online application[(1)],we've converted the text strings into their corresponding hexadecimal values.





The TELECOM text is converted to HEXADECIMAL using the preceding line conversion in the manner shown below.

(1) https://magictool.ai/tool/text-to-hex-converter/fr/

T	E	L	E	C	O	M
54	**45**	**4C**	**45**	**43**	**4F**	**4D**

The LICENCE text is converted to HEXADECIMAL using the preceding line conversion in

L	I	C	E	N	C	E
4C	**49**	**43**	**45**	**4E**	**43**	**45**

the manner shown below.

To write data to the tag, follow these steps:

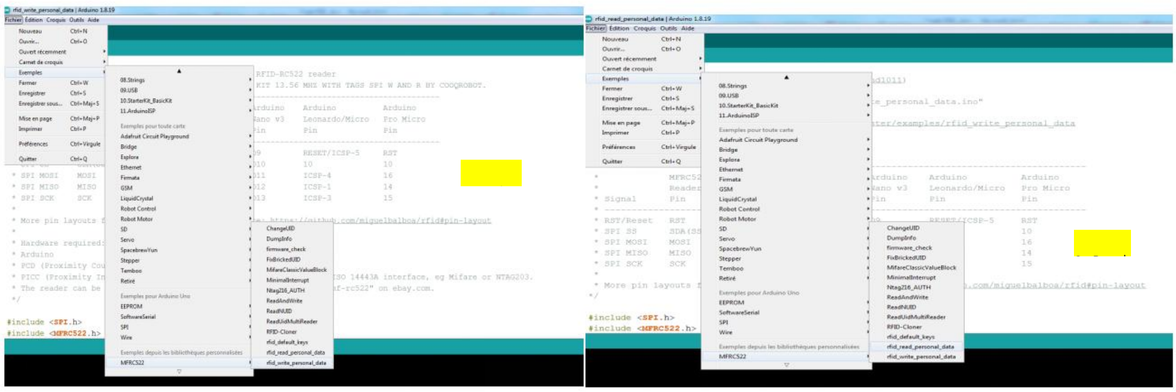
1- Program of writing in the RC522 library:

✓ For writing to the tag, we have selected the **rfid_Write_ personal_data** application.

In order to read the data in the tag, follow these steps:

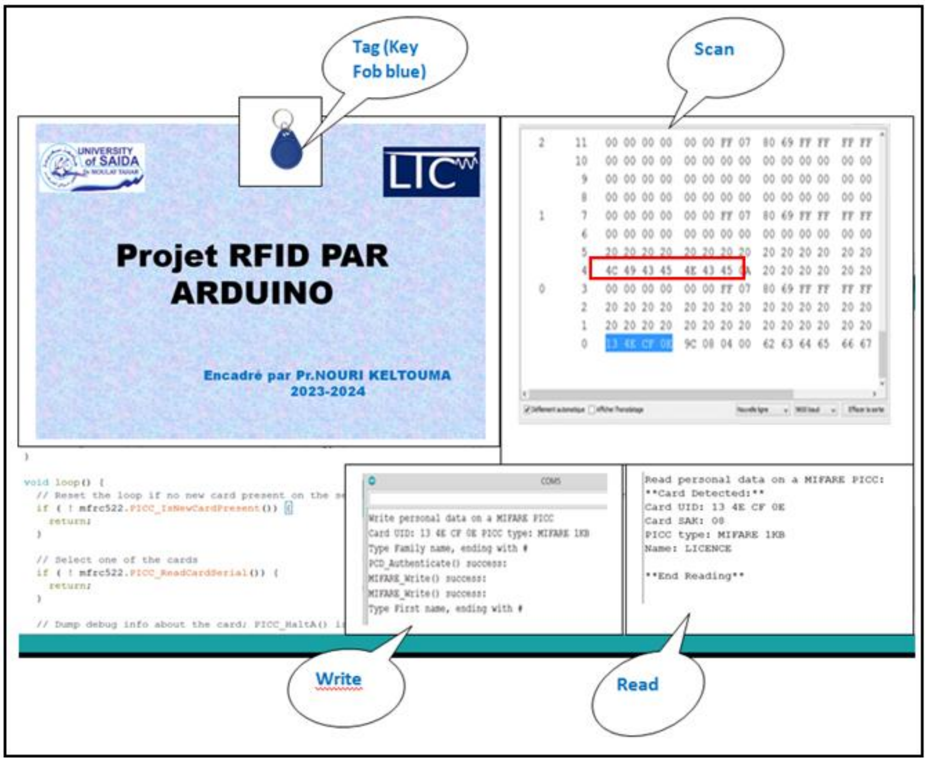
2- Select the reading software in the RC522 library.

✓ Similarly, we have selected the software **rfid_read_personal_data** to be written on the envelope.



Result :

Blue key ring identifier :



Card identification (UID):