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A circularly polarized reader antenna dedicated for handheld UHF/SHF deployments: study and design

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Dedications

We could not have taken our first steps without His guidance, nor reached our goals without His assistance, nor achieved our purpose without His grace. Praise be to God, who has guided me to take this step in my academic journey.

I dedicate the fruit of my labor to my own ambitious self, who has never let me down. I extend my sincere thanks and appreciation to my dear parents, who have been my constant support and pillar of strength; it is through their prayers, patience, and love that I have reached this special moment in my life.

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Dedications

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Abstract

A dual-band circularly polarized (CP) reader antenna for handheld RFID applications is presented, operating in the UHF (0.915 GHz) and SHF (2.45 GHz) bands. The antenna is implemented on a 1.6 mm thick FR4 substrate with overall dimensions of 85 × 85 × 1.6 mm^3. It consists of two crossed-dipole elements printed on the top and bottom surfaces, oriented orthogonally to generate CP radiation. The antenna is fed via a coaxial cable at the middle with an impedance of 50 Ω. The reader antenna achieves circularly polarized radiation at frequencies of 0.915 GHz and 2.45 GHz, with gain values of 1.87 dBi and 1.522 dBi, respectively. To extend the reading range, a frequency-selective surface (FSS) is employed as a reflector, with its dimensions and the separation distance from the antenna carefully optimized. The results of the proposed reader over the FSS reflector show that the gain is improved to 7.86 dBi at 0.915 GHz and 8.32 dBi at 2.45 GHz. The proposed antenna integrated with the FSS reflector is, therefore, an excellent choice for handheld RFID readers, combining compact mobility with significantly improved read range.

Keywords–RFID, Reader antenna, UHF/SHF band, Miniaturization, Circularly polarized antenna, frequency-selective surface (FSS), Reading range.

Résumé

Nous présentons une antenne lecture à double bande et à polarisation circulaire (CP), destinée aux applications RFID portables, fonctionnant dans les bandes UHF (0,915 GHz) et SHF (2,45 GHz). L'antenne est imprimée sur un substrat FR4 de 1,6 mm d'épaisseur, avec des dimensions globales de $85 \times 85 \times 1,6\ mm^3$. Elle se compose de deux éléments dipôles croisés imprimés sur les faces supérieure et inférieure, orientés orthogonalement pour générer un rayonnement à polarisation circulaire. L'antenne est alimentée par un câble coaxial au centre, avec une impédance de 50 Ω. L'antenne lecture produit un rayonnement à polarisation circulaire aux fréquences de 0,915 GHz et 2,45 GHz, avec des gains respectifs de 1,87 dBi et 1,52 dBi. Afin d'étendre la portée de lecture, une surface sélective en fréquence (FSS) est utilisée comme réflecteur, dont les dimensions et la distance de séparation par rapport à l'antenne ont été soigneusement optimisées. Les résultats de l'antenne avec le réflecteur FSS montrent que le gain est amélioré à 7.86 dBi à 0,915 GHz et à 8,32 dBi à 2,45 GHz. L'antenne proposée, intégrée au réflecteur FSS, constitue donc un excellent choix pour les lecteurs RFID portables, alliant une mobilité compacte à une portée de lecture nettement améliorée.

Mots clés– RFID, Antenne lecteur, bande (UHF/SHF), Antenne à polarisation circulaire, surface sélective en fréquence (FSS), Portée de lecture.

ملخص

يتم عرض هوائي قارئ ثنائي النطاق ذي استقطاب دائري CP مخصص لتطبيقات RFID المحمولة، يعمل في نطاقي الترددات فوق العالية UHF (0.915 جيجاهرتز) والترددات فائقة العالية SHF (2.45 جيجاهرتز) . تم تنفيذ الهوائي على ركيزة FR4 بسمك 1.6 مم بأبعاد إجمالية تبلغ $85 \times 85 \times 1.6\ mm^3$. ويتكون من عنصرين ثنائي القطب متقاطعين مطبوعين على السطحين العلوي والسفلي، وموجهين بشكل متعامد لتوليد إشعاع CP . يتم تغذية الهوائي عبر كابل المحور في المنتصف بمقاومة تبلغ 50Ω . تحقق هوائي القارئ إشعاعًا مستقطبًا دائريًا عند ترددات 0.915 جيجاهرتز و 2.45 جيجاهرتز، بقيم كسب تبلغ 1.87 ديسيبل و 1.52 ديسيبل، على التوالي. لتوسيع نطاق القراءة، يتم استخدام سطح انتقائي التردد FSS كعاكس، مع تحسين أبعاده ومسافة الفصل عن الهوائي بعناية. تُظهر نتائج القارئ المقترح فوق عاكس FSS أن الكسب قد تحسّن إلى 7.86 ديسيبل عند 0.915 جيجاهرتز و 8.32 ديسيبل عند 2.45 . وبالتالي، فإن الهوائي المقترح المدمج مع عاكس FSS هو خيار ممتاز لقارئات RFID المحمولة، حيث يجمع بين الحجم الصغير وسهولة التنقل مع نطاق قراءة محسّن بشكل ملحوظ.

الكلمات المفتاحية RFID ، هوائي العلامة، هوائي القارئ، نطاق UHF/SHF ، هوائي مستقطب دائريًا، سطح انتقائي التردد FSS ، الكسب .

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List of Acronyms and Abreviations

CST	Computer Simulation Technology
EPC	Electronic Product Code
ERP	Effective Radiated Power
ERIP	Equivalent Isotropically Radiated Power
ETSI	European Télécommunication Standards Institute
HF	High Frequency
ID	Identification
ISO	Organization International de Normalization
LBT	Listen Before Talk
LF	Low Frequency
LHCP	Left Handed Circular Polarization
AR	Axial ratio
RF	Radio Frequency
RFID	Radio Frequency Identification
RHCP	Right Handed Circular Polarization
SHF	Super High Frequency
UHF	Ultra High Frequency
VSWR	Voltage Standing Wave Ratio
FSS	Frequency selective surfaces

List of Symbols

f_1	Lower frequency
f_2	Higher frequency
Z_C	Characteristic impedance
$\Gamma(x)$	The reflection coefficient on a line
s_{11}	The reflection coefficient at the entrance to the antenna
Δ f	Bandwidth
η	Radiation efficiency
$F(\theta,\varphi)$	Radiation characteristic function
$P(\theta,\varphi)$	Power in the direction(θ,φ)
$P(\theta_0,\varphi_0)$	Power in direction of maximum radiation
$D(\theta,\varphi)$	Directionality in direction (θ,φ)
$G(\theta,\varphi)$	Gain in direction (θ,φ)
P_t	Input power
P_r	Power at reception
G_t	Gain the transmitting antenna
G_r	Gain of receiving antenna
E	The electric field vector
E_x	The component of the electric field vector in the x direction
E_y	The component of the electric field vector in the y direction
f	The frequency in Hertz
ω	The pulsation in radians per second, equal to $2\pi f$
k	The wave number in radians per meter
φ_x	The initial phase of the E_x component
φ_y	The initial phase of the E_y component
τ	Transmission coefficient
G_t	Gain of the transmitting antenna
G_r	Gain of the receiving antenna
G	Gain
D	Directivity
Z_{Chip}	Chip impedance
λ	Wavelength

General Introduction

Radio frequency identification (RFID) is considered one of the most pervasive computing technologies in history [1]. However, the RFID concept is not new but has been around for decades; in fact, it was introduced to the world for the first time during World War II by the British Air Force to distinguish Allied aircraft from enemy aircraft. Radio Frequency Identification (RFID) technologies are becoming increasingly prevalent in everyday life. RFID is used in numerous applications across a wide range of industries. Despite the enthusiasm surrounding this technology, it faces a number of obstacles. To address various challenges, Tagsys RFID has launched the SPINNAKER project. The project's ambition is to overcome significant technological limitations across various areas. The first concerns UHF and SHF band RFID technology, in which Tagsys, RFID aims to develop fixed RFID readers and associated antennas. The aim is to improve tag localization and detection to enable better logistics tracking and simplified inventory management, regardless of the application environment (warehouse, hospital, retail outlets) [2].

Spatial filters, also known as frequency selective surfaces (FSS), are structures used to control the propagation of electromagnetic waves by modifying their transmission and reflection characteristics. These surfaces are usually realized using periodic metallic patterns printed on a dielectric substrate. Depending on their design, FSS can affect the transmitted wave by changing its amplitude and phase compared to the incident wave. In addition, polarization selectivity can be introduced in order to improve the radiation pattern and reduce unwanted distortions. In general, the electromagnetic response of FSS structures can be adapted according to the required application, which makes them suitable for different uses such as filtering and antenna enhancement [3].

The RFID reader antennas in the literature encounter several issues, most notably that they operate in limited reading range with high polarization losses due to misalignment between readers and tags [4]. In this work, we attempted to improve these shortcomings by proposing a dual-band RFID antenna with a circularly polarized field, along with an increase in gain by using a frequency selective surface (FSS). This work focuses on designing a small-sized antenna based on an FSS-type reflector to enhance the reading range in RFID applications. The CST Microwave Studio software tool is used to simulate and design the proposed structure, which helped us improve and optimize the antenna performance, making it suitable for various RFID applications.

In the first chapter, we address the fundamentals of RFID antennas, by explaining the most important electrical parameters such as impedance, Standing Wave Ratio (SWR), and bandwidth, in addition to radiation parameters such as gain, directivity, and radiation pattern, because they are essential for understanding antenna performance. The principle of frequency selective surfaces (FSS) and their role in improving antenna performance in terms of controlling electromagnetic response is also discussed.

In the second chapter, we tried to delve into RFID systems in order to understand their structure and how they work more clearly. The focus was on the basic components of the system and the operating principle in a simplified scientific manner, along with addressing the laws and standards regulating the use of this technology.Various application areas of RFID technology were also reviewed, highlighting the main advantages it provides in several applications, in addition to some limitations or deficiencies that may affect its performance in certain cases.

In chapter three, the proposed antenna design was addressed, where the various design stages and scenarios used in this work were presented. After that, the results obtained through simulation were presented, along with their analysis and discussion in a way that explains the antenna's performance and effectiveness, in addition to interpreting the be-

havior observed during the study.

We conclude this work with a general conclusion in which the most important results reached during this work are summarized, highlighting the main points that were achieved. Future work prospects and possible directions for further developing the study in upcoming projects are also addressed.

Chapter 1

Antenna fundamental parameters

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1.1 Introduction

Focusing on the antenna as a key component in Radio Frequency Identification (RFID) systems, this chapter examines the fundamental elements of antennas and their applications. Antennas are responsible for transmitting and receiving electromagnetic signals through space [5], effectively serving as the final stage of the transmission chain. Most reader antennas on the market today operate within a specific frequency band, typically one of the five internationally recognized RFID frequency bands. The chapter concludes with a summary demonstration of frequency selective surfaces (FSS) technology, which offers advanced capabilities in controlling electromagnetic wave propagation.

1.2 Antenna principle

The purpose of an antenna is to transform the electrical energy of a signal into electromagnetic energy carried by an electromagnetic wave (or inversely). A conventional definition is as follows: An antenna d'ésission is a device that ensures the transmission of energy between an emitter and the free space where this energy will propagate. Conversely, an antenna of reception is a device that ensures that the energy of an oscillation traveling across space is sent to a receiving device [6].

1.2.1 Electrical parameters

The Electrical parameters of an antenna are defined in terms of its connection to the circuit to which it is attached. They allow the charge applied by the antenna to the excitation circuit to be evaluated, thereby determining the efficiency of energy transfer between the radio-electric system and the propagation environment. Parameters that can be used to describe this include: reflection coefficient, station stability ratio, bandwidth, noise temperature, etc [5].

1.2.1.1 Bandwidth

The frequency range in which the reflection coefficient remains below a certain threshold is called the antenna bandwidth or pass-through range. It can also be defined as the frequency range in which the power transmitted between the antenna and the power source (or from the antenna to the receiver) exceeds a predetermined threshold, thus ensuring proper compatibility between the antenna and the excitation source.

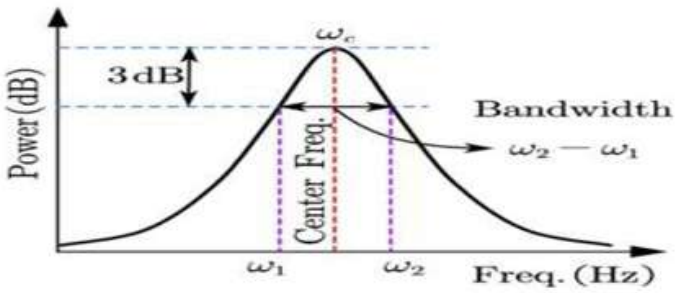

Figure 1.1: The bandwidth [7].

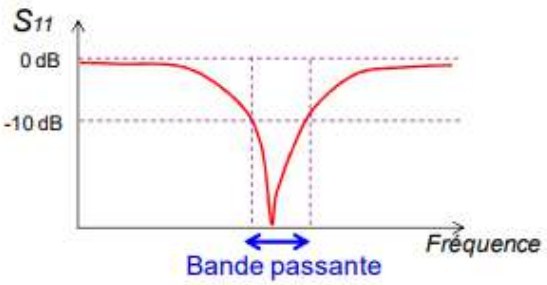

Figure 1.2: Antenna bandwidth estimation.

As seen in Figure 1.1, the bandwidth is defined as the frequency range where the VSWR does not surpass the designated threshold and the power [8–10] gain does not decrease by more than 3 dB from its peak value [5].

Figure 1.2 shows how to calculate the antenna bandwidth from the reflection coefficient curve (s_{11}) using specific standard parameters. The power transmission range is restricted to -3 dB, -6 dB, -10 dB, or -15 dB, with -10 dB being significant as it indicates 90% of source power is transmitted and10% is reflected, usually at frequencies far from the antenna's center frequency. The frequency range is denoted Δf, and is given by:

$$\Delta f = f_2 - f_1 \tag{1.1}$$

1.2.1.2 Reflection coefficient and standing wave rate

The reflection coefficient is a parameter that measures the ratio of the reflected signal to the incident signal. In general, this coefficient Γ related to the antenna input impedance (Ze) and the characteristic impedance (Zc) by the relationship [11]:

$$\Gamma = \frac{Z_e - Z_c}{Z_e + Z_c} \tag{1.2}$$

One way to express the coefficient Γ in terms of the coefficient S in decibels is as follows [5]:

$$\Gamma\,(\mathrm{dB}) = S_{11}\,(\mathrm{dB}) = 20\log|S_{11}| \tag{2.3}$$

The voltage standing wave ratio (VSWR), which is the ratio of the maximum voltage to the minimum voltage, can also be calculated [5]:

$$\mathrm{VSWR} = \frac{V_{max}}{V_{min}} = \frac{1+|\Gamma|}{1-|\Gamma|} \tag{1.3}$$

1.2.1.3 Transmission coefficient

The ratio of the power transferred to the load to the maximum total power that can be transferred to it is expressed by the transfer coefficient T. This relationship can be used to determine the transfer coefficient [5, 12]:

$$T = 1 - |\Gamma|^2 \tag{1.4}$$

1.2.1.4 Quality factor

The quality factor is a fundamental parameter for an antenna, and its definition is derived from its analogy with linear electronic circuits. The quality factor depends on the frequency band and is typically calculated at the resonant frequency. This frequency represents the characteristics of the antenna.Thus, the total quality factor is affected by all these types of losses and is expressed by [13–15]:

$$\frac{1}{Q_t} = \frac{1}{Q_{rad}} + \frac{1}{Q_c} + \frac{1}{Q_d} + \frac{1}{Q_{sw}} \tag{1.5}$$

where:
Q_t = total quality factor.
Q_{rad} = quality factor due to radiation(space wave) losses.
Q_c = quality factor due to conduction (ohmic) losses.
Q_d = quality factor due to dielectric losses.
Q_{sw} = quality factor due to surface waves.

1.2.2 Radiation parameters

An antenna's radiation characteristics explain how it sends and receives electromagnetic waves in space. These are some of the most crucial aspects of radiation.

1.2.2.1 Radiation pattern

The characteristics of an antenna's radiation, as a function of spatial coordinates, are represented mathematically or graphically by the antenna's radiation pattern, or simply the antenna mode. Antenna radiation patterns are typically found in the far-field region. In this region, the angular field distribution is practically unaffected by the distance from a given point in the antenna region.

The following subsections discuss these parameters: polarization phase, axial ratio, tilt angle, orientation or partial orientation, mode function or one of its components, or gain or partial gain [16].

1.2.2.2 Radiation characteristic function

The radiation characteristic function, denoted $F(\theta,\phi)$, represents the energy emitted from an antenna in specified directions defined by angles θ and ϕ, relative to the maximum power $P(\theta_0,\phi_0)$radiated by the same antenna. The RCF varies between 0 and 1 based on direction, the radiation characteristic function can be expressed as follows [5]:

$$F(\theta,\phi) = \frac{P(\theta,\phi)}{P(\theta_0,\phi_0)} \tag{1.6}$$

In general, radiation patterns appear in three basic types:

a) Isotropic radiation

An isotropic radiator is defined as a hypothetical lossless antenna having equal radiation in all directions. Although it is ideal and not physically realizable. It is often taken as a reference to express the directive properties of the actual antennas.

b) Directional radiation

A directional antenna is one having the property of radiating or receiving electromagnetic

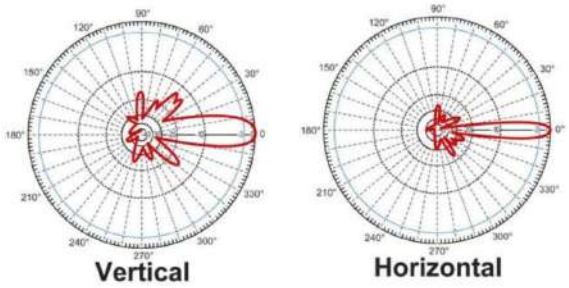

Figure 1.3: Isotropical radiation pattern in vertical and horizontal planes.

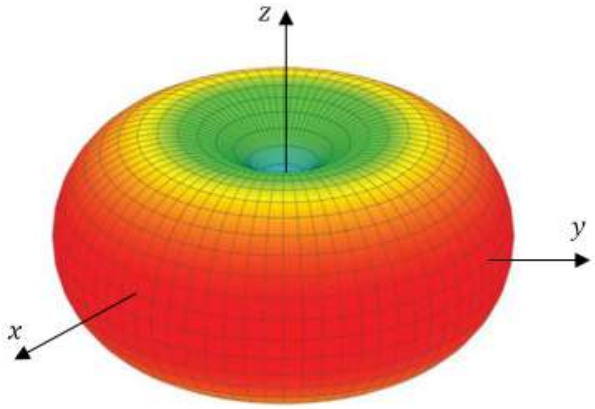

Figure 1.4: Omnidirectional radiation pattern.

waves more effectively in some directions than in others. This term is usually applied to an antenna whose maximum directivity is significantly greater than that of a half-wave dipole.

c) Omnidirectional radiation

Directional antennas are those that radiate or receive electromagnetic waves more effectively in certain directions compared to others, typically exhibiting greater maximum directivity than a half-wave dipole. Omnidirectional antennas, a subtype, have a non directional pattern in one plane while being directional in orthogonal planes in Figure 1.4.

1.2.2.3 Angle of opening

The angle of opening is crucial as it defines the size of the main lobe, with the -3 dB angle (2θ) indicating the space where most power is radiated. This angle is determined by the distance between two directions from the main lobe where the power is half of that radiated in the peak direction in Figure 1.5 [6].

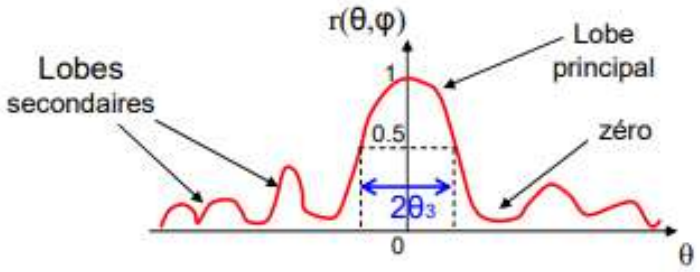

Figure 1.5: Angle of opening.

1.2.2.4 Antenna directivity

Directivity in a direction, D(θ,ϕ)is defined by the ratio of the power intensity radiated in a specific direction to the total radiated power intensity of an isotropic antenna [17].

$$D(\theta,\varphi) = \frac{U(\theta,\varphi)}{P_r/4\pi} \tag{1.7}$$

1.2.2.5 Antenna gain

Antenna gain is a key indicator for measuring system performance. Antenna gainG(θ,ϕ) is represented as the ratio of U(θ,ϕ) to the power per unit stereoscopic angle emitted by the antenna if it is isotropic, provided that the allowable power P_{ant} is equal [18].

$$G(\theta,\varphi) = \frac{U(\theta,\varphi)}{P_a/4\pi} \tag{1.8}$$

1.3 Friis transmission equation

One of the most important equations in communication system is the Friis transmission equation. The gain antenna G_t which is powered by the P_t and received by the G_r gain antenna, is connected to a distance from the transmitting antenna. Radiated energy density at a vacuum distance:

$$p_r = \frac{P_t G_t}{4\pi d^2} \tag{1.9}$$

At a distance d, the power received, P_r, by a surface reception antenna equal to A_r is as follows:

$$P_r = p_r A_r, \text{where } A_r = \frac{G_r \lambda^2}{4\pi} \tag{1.10}$$

Thus, the Friis equation for telecommunication is:

$$P_r = P_t G_t G_r \left(\frac{\lambda}{4\pi d}\right)^2 \tag{1.11}$$

The attenuation of the relationship can be A_0 decreased:

$$A_0 = \frac{P_r}{P_t} = \left(\frac{\lambda}{4\pi d}\right)^2 \tag{1.12}$$

The propagation loss is the first component of the transmission equation [5].

1.4 Field polarization

The polarization of an antenna refers to the spatial direction of the electric field vector of the emitted electromagnetic wave, particularly in the far field, indicating where field intensity is at its maximum. The instantaneous field of a plane wave, traveling in the negative z direction, can be written as:

$$\mathrm{E}(z,t) = \hat{x}\mathrm{E}_x(z,t) + \hat{y}\mathrm{E}_y(z,t) \tag{1.13}$$

The instantaneous components are related to their complex counterparts by:

$$\mathrm{E}(z,t) = \hat{x}\mathrm{E}_{x_0}\cos(wt - kz + \varphi_x) + \hat{y}\mathrm{E}_{y_0}\cos(wt - kz + \varphi_y) \tag{1.14}$$

Where, E_{x_0} and E_{y_0} are respectively the maximum magnitudes of the x and components, three types of polarization are briefly described below.

a)Linear polarization

For the linearly polarized wave, the time-phase difference between the two components must be [19]:

$$\Delta\varphi = \varphi_y - \varphi_x = n\pi, n = 0,1,2,3,... \tag{1.15}$$

Consequently, it is expressed as follows in trigonometric form:

$$\mathrm{E}(z,t) = \hat{x}\mathrm{E}_{x_0}\cos(wt - kz) \pm \hat{y}\mathrm{E}_{y_0}\cos(wt - kz) \tag{1.16}$$

Figure 1.6 clearly shows the direction of the electric field vector in the case of linear polarization.

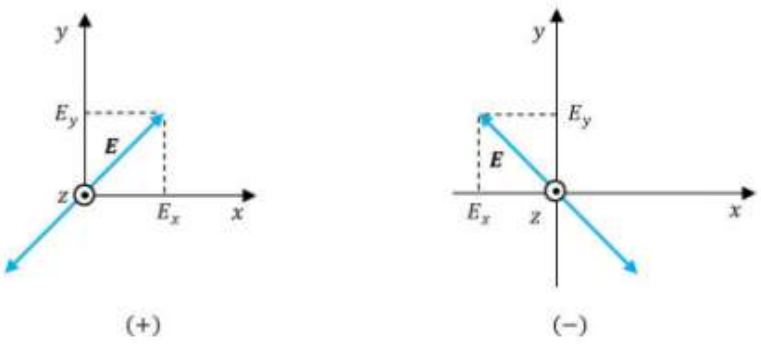

Figure 1.6: Cartesian representation of linear polarization.

b)Circular Polarization

Circular polarization [20, 21] can be achieved only when the magnitudes of the two components are the same and the time-phase difference between them is odd multiples of $\pi/2$, as shown in the figure 1.7.

$$\mathrm{E}_{x_0} = \mathrm{E}_{y0} \tag{1.17}$$

$$\Delta\varphi = \varphi_y - \varphi_x = n\pi = \begin{cases} +(\frac{1}{2}+2n)\pi, n = 1,2,... & \text{for CW} \\ -(\frac{1}{2}+2n)\pi, n = 1,2,... & \text{for CCW} \end{cases} \tag{1.18}$$

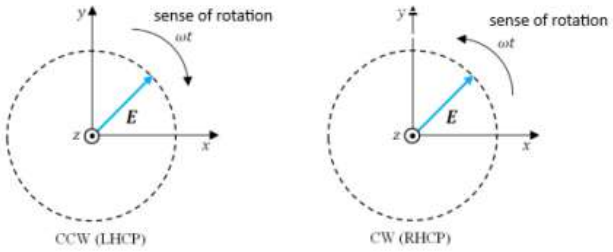

Figure 1.7: Cartesian representation of circular polarization.

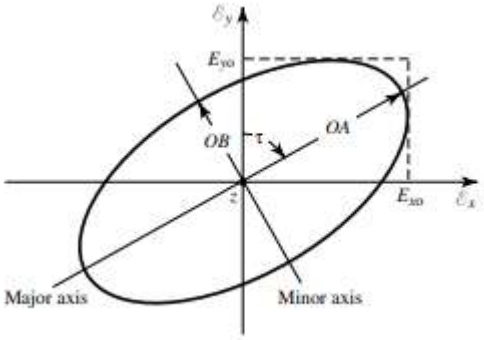

Figure 1.8: Polarization ellipse.

c)Elliptical Polarization

Elliptical polarization can be attained only when the time-phase difference between the two components is odd multiples of $\pi/2$ and their magnitudes are not the same or when the time-phase difference between the two components is not equal to multiples of $\pi/2$. That is,

$$E_{x0} \neq E_{y0} \tag{1.19}$$

$$\Delta\varphi = \varphi_y - \varphi_x = n\pi = \begin{cases} +(\frac{1}{2}+2n)\pi, n = 1,2,\ldots & \text{for CW} \\ -(\frac{1}{2}+2n)\pi, n = 1,2,\ldots & \text{for CCW} \end{cases} \tag{1.20}$$

For elliptical polarization, [19] the curve traced at a given position as a function of timeis, ingeneral, a tilted ellipse, as shown in Figure 1.8 . The ratio of the major axis to the minor axis is referred to as the axial ratio (AR), and it is equal to:

$$AR = \frac{\text{major axis}}{\text{minor axis}} \tag{1.21}$$

Polarisation is circular when AR = 1. The polarisation is linear when AR is infinite. AR is frequently expressed in dB:

$$AR_{dB} = 20\log(AR_{\text{linear}}) \tag{1.22}$$

Polarisation is circular when AR = 1. The polarisation is linear when AR is infinite.

1.5 Radiation efficiency

The portion of power lost between the RF source and the propagation medium is measured by an antenna radiation efficiency, η, It is often understood to be the ratio of the feed power P_a to the total radiating power P_r [22].

$$\eta = \frac{P_r}{P_a} \tag{1.23}$$

The directivity in real values is related to the gain by:

$$G(\theta,\phi) = \frac{U(\theta,\phi)}{P_a/4\pi} = \eta\frac{U(\theta,\phi)}{P_r/4\pi} = \eta D(\theta,\phi) \tag{1.24}$$

1.6 Frequency selective surfaces (FSS)

In time-domain systems, spatial filtering is the only critical element, where frequency selectivity (FSS) acts as a spatial filter that modulates the phase of the electromagnetic wave, like as shown in Figure 1.9. These filters consist of periodic metallic layers on a dielectric substrate and can enhance selectivity against polarization, thus improving emission selection [23]. The feed signal is split into distinct bands by FSS reflectors [24]. The kind of array member determines whether the incoming plane wave is transmitted(pass-band) or reflected (stopband) 1.9.

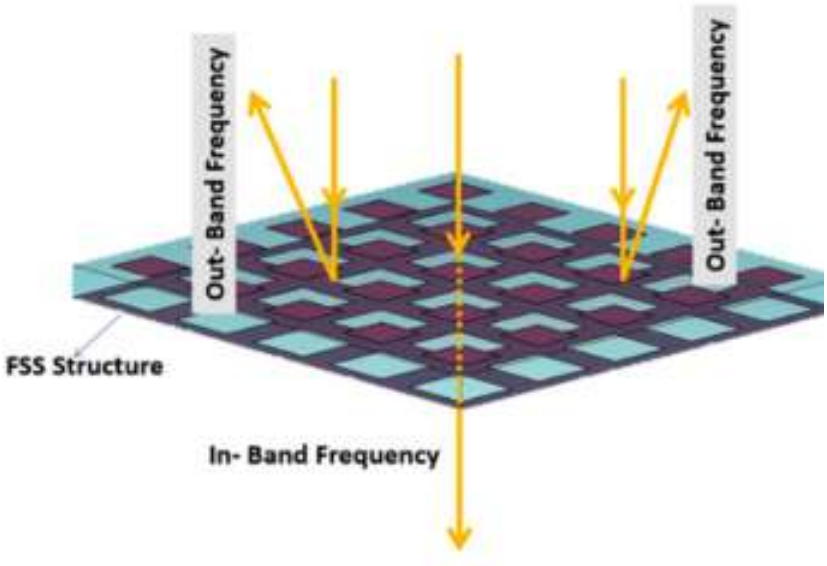

Figure 1.9: FSS functionality.

1.7 Commonly used FSS element geometries

The commonly used geometry in the design of FSS unit cells are shown in Figure 1.10 and categorized in four groups.

- Group-1: contains patterns consisting of a dipole, tripolar, square helix, cross-pole, or north pole.

- Group-2: includes patterns in which circular, square, and hexagonal loops are repeated.
- Group-3: contains patches of various shapes filled from within.
- Group-4: includes patterns grouped in various configurations [25].

The designer of frequency-selective surfaces selects a matrix element from one of these groups or uses a combination of them, depending on the intended application. A good element should respond to changes in incidence angles with a steady resonance. Because it increases the bandwidth, using a Group-2 element with a larger loop area can sometimes be advantageous [26]. To move loaded objects with three or four legs forward, basic circular loops and Square loops have been employed; for wide band applications, hexagonal loop topologies are particularly useful.

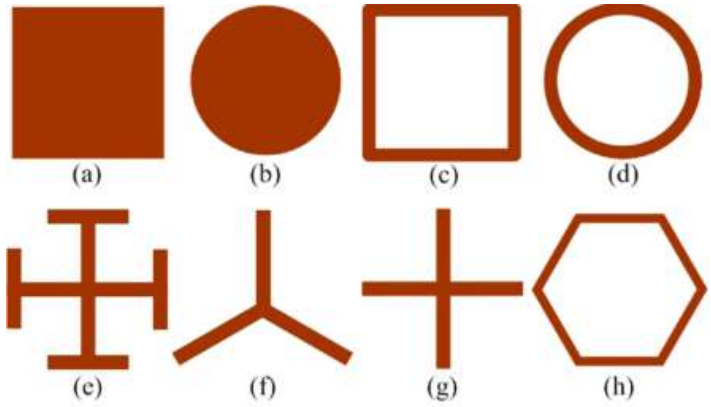

Figure 1.10: Common FSS element geometries.

1.8 Classification of frequency-selective surfaces

A grid of periodic metal patterns placed on a substrate is known as a frequency selective surface (FSS). FSS is typically separated into two categories: mesh FSS and etch FSS [27]. At low frequencies, these structures reflect precisely, acting like nearly perfect mirrors. Just utilize the wire mesh [28] as illustrated in Figure 1.11 to create these metallic structures. Below, a high-pass filter and a low-pass filter can work well together. A patch grid, a Babin network complement to the low-pass filter depicted in the image, is demonstrated in the picture. IL appears as a periodic planar array of metal rings in the FSS bandstop. An arrangement of ring-shaped slots makes up the FSS band-pass [29], a metal grid that is the opposite of band-cutting.

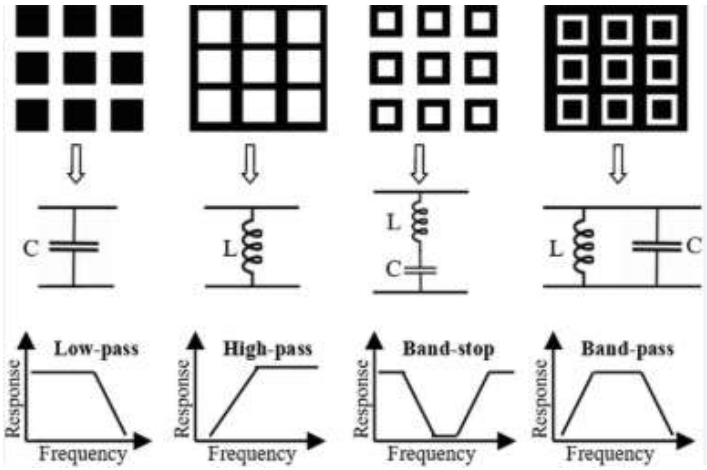

Figure 1.11: Frequency-selective surface classification.

1.9 Conclusion

This chapter has focused on defining the fundamental parameters of antennas, detailing their electrical and radiation characteristics, and offering a comprehensive overview of their performance. In addition, frequency-selective surfaces (FSS) have benn introduced, classified, and defined. These structures function as spatial filters, passing desired frequency bands while blocking unwanted ones.

Chapter 2

Radio-frequency identification systems overview

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2.1 Introduction

Radio frequency identification (RFID) technology is used in lot of domains, including public transportation, manufacturing, logistics, and other industries due to its advantages in terms of low cost, high reading range, flexibility, and durability. An RFID system typically consists of several tags and readers. The reader sends an electromagnetic wave to activate the tag. When activated, the tag collects requests from readers and responds by switching its antenna load. In this chapter, we discuss the types of known identification systems. We highlight RFID technology, focusing on some general concepts of this technology, known types of identification, the principle of RFID operation, and its most important components. We explore passive UHF systems and RFID applications, concluding with their advantages and disadvantages [30].

2.2 RFID systems

Radio Frequency Identification (RFID) technology is a modern technology that enables the tracking of the movement of objects or people [31] . A typical RFID system consists of cards (also known as transceivers, smart cards, smart tags, or wireless barcodes), a reader (also called a writer, decoder, interrogator, transmitter, receiver, or transceiver), and software/infrastructure [32]. The reader exchanges information with the central computer via a wired or wireless connection, as illustrated in Figure 2.1 [33].

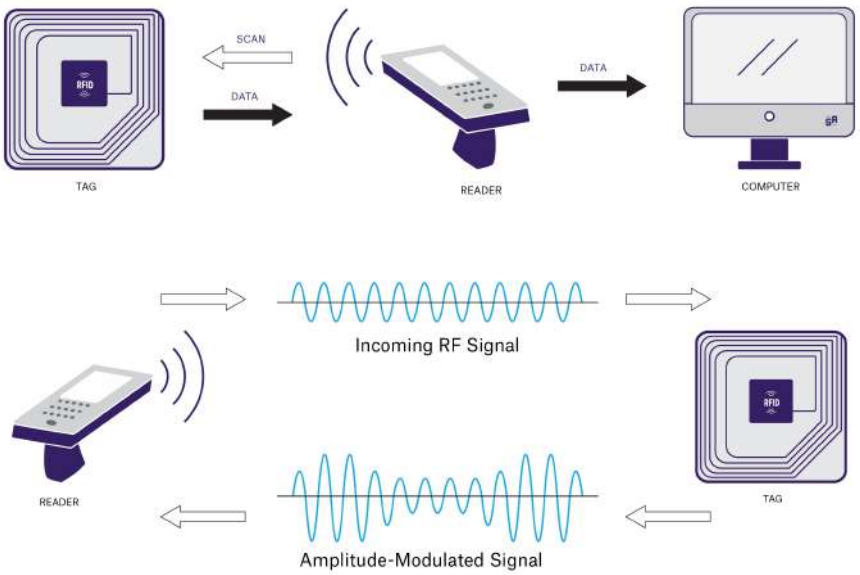

Figure 2.1: RFID system principle.

RFID technology offers several key advantages over traditional barcodes:

- No direct line of sight needed – Tags can be read even when covered, embedded, or in harsh conditions, unlike barcodes that require a clean, visible surface.
- Greater data storage – RFID chips hold a unique EPC identifier and can include rewritable user memory for storing and updating process data over time.

- Simultaneous scanning – Multiple items can be read at once from various angles, enabling rapid bulk scanning and saving significant time.

- Enhanced data protection – Modern encryption and shielding address earlier security concerns, helping keep sensitive information confidential and making tags tough to clone.

2.3 RFID components

A radio frequency identification (RFID) system consists of two components [34]:

- Transponder, which is located on the object to be identified.

- Interrogator or reader, depending upon the design and the technology used.

2.4 RFID reader

In order to gather identifying information, RFID readers use a radio frequency (RF) channel to connect with RFID tags. In order to extract tag IDs, RFID readers usually have two interfaces: an RF interface for interacting with tags within their read range and a communication interface for connecting servers, often IEEE802.11 or 802.3. There are two types of RFID readers: mobile and fixed reader [35].

2.4.1 Mobile reader

Mobile RFID readers are what are known as handheld readers, as shown in Figure 2.2 Handheld readers consist of built-in antennas and do not usually have additional antenna connectors. They are battery-powered, lightweight, and can provide much shorter read ranges than fixed readers (up to 100 m). Handheld readers are used to track live livestock (farm animals such as sheep, goats, and cows) and locate items in warehouses, inventory, etc. They connect to a host computer using wireless communication protocols and contain memory blocks for storing data. Handheld RFID readers [36, 37].



Figure 2.2: Mobile RFID reader.

2.4.2 Fixed reader

The fixed RFID reader, Figure 2.3, is installed in gate systems through which the tags pass. In order to detect the tags, the reader's antenna must meet certain specifications: circular polarization, directional radiation with low side lobes so as not to detect tags near the reading area, and high gain to sufficiently detect tags at a reasonable distance [38].



Figure 2.3: Fixed reader.

2.5 RFID Tag

An RFID tag is a small electronic device also referred to as a transceiver. The tag consists of a simple silicon chip and an antenna. The tag can be attached to an object, usually an item or a box. Information is collected by the chip and can be transmitted wirelessly. RFID tags come in three different configurations: active(with batteries), passive (without batteries), or semi-passive (hybrid). The tag contains an identification code that can be transmitted to a reader. The different types of tags are shown in the Figure 2.4 [39].

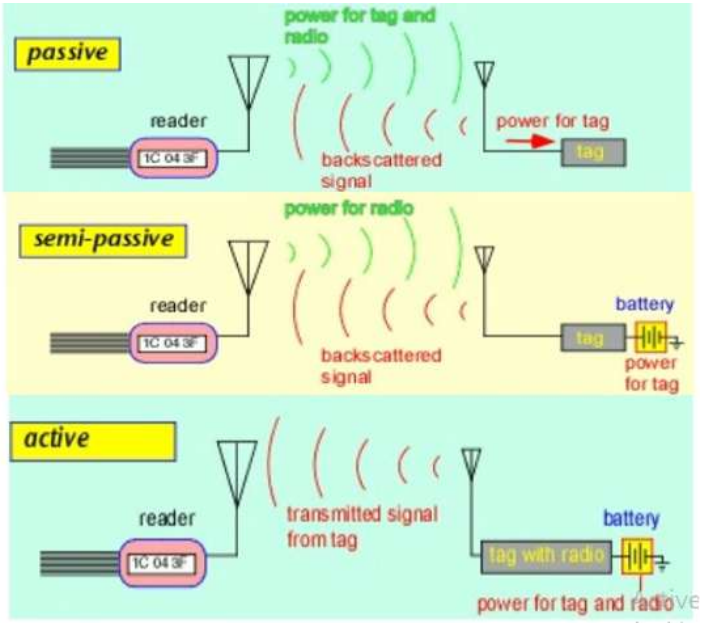

Figure 2.4: Type of RFID Tags.

2.5.1 Types of RFID Tags

2.5.1.1 Passive RFID tags

A passive tag responds to an interrogator by using the electromagnetic energy it receives from their transmission. Only a small portion of the interrogator's signal strength is present in the reply signal from a passive tag, also referred to as the backscattered signal. The tag functioning range is severely constrained by this low power. Passive tags can only handle data processing of a restricted complexity because they are low power devices. However, compared to other tag types, passive tags are usually less expensive, lighter, and smaller, which are strong benefits for a variety of RFID applications. Passive Tag is show in Figure 2.5 [40].

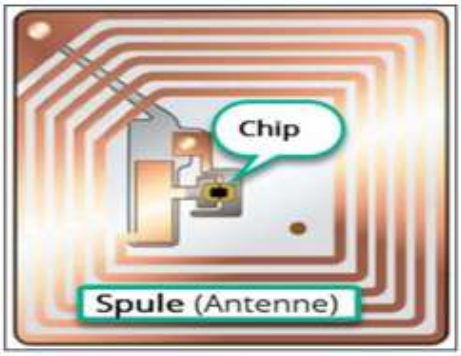

Figure 2.5: **Passive RFID .**

2.5.1.2 Active RFID Tag

An active tag relies on an internal battery for power. The battery is used to communicate to the interrogator, to power on-board circuitry, and to perform other functions. Active tags can communicate over greater distance than other types of tags, but they have a finite battery life and are generally larger and more expensive. Since these tags have internal power, they can respond to lower power signals than passive tags. An active RFID tag is show in Figure 2.6 [40].

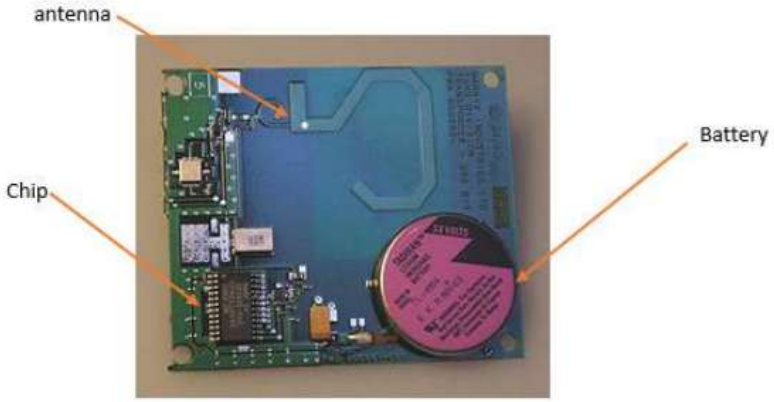

Figure 2.6: **active RFID Tag.**

2.5.1.3 Semi-passive RFID Tag

A semi-passive tag is a passive tag that uses a battery to power on-board circuitry, but not to produce return signals. When the battery is used to power a sensor, it is often called a sensor tag. It is typically smaller and cheaper than an active tag, but has greater functionality than a passive tag due to the availability of more power for other purposes. Some literature uses the terms “semi-passive” and “semi- active” inter- changeably. as shown in Fig 2.7 [40].



Figure 2.7: **Semi-passive RFID Tag.**

2.6 Operating principle of RFID systems

Every RFID system consists of three components: a scanning antenna, a transceiver, and a transceiver. The transceiver and antenna assembly is called the RFID reader. An RFID reader is a network-connected device that uses radio waves to provide pulses that activate the card. When the card is activated, a signal is sent to the antenna, which converts it into data.

2.6.1 Operating frequency and reading range for RFID systems

Radio frequency identification (RFID) signals fall between electrical signals and infrared radiation. RFID systems are typically classified based on the frequency band in which they operate. The frequency band length indicates the type of radio waves used to communicate with system components, and each frequency band has its own operating range. Figure 2.8 illustrates the main frequency bands used in RFID systems [41].

Table 2.1: RFID frequency bands and typical reading distances.

Frequency	Designation	Range
125 and 134.2 KHz	Low Frequency (LF)	10–20 cm
13.56 MHz	High Frequency (HF)	1 m
433 MHz	Ultra-High Frequency (UHF)	100 m
860–960 MHz	Ultra-High Frequency (UHF)	1–2 m
2.45 and 5.8 GHz	Super-High Frequency (SHF)	1–2 m

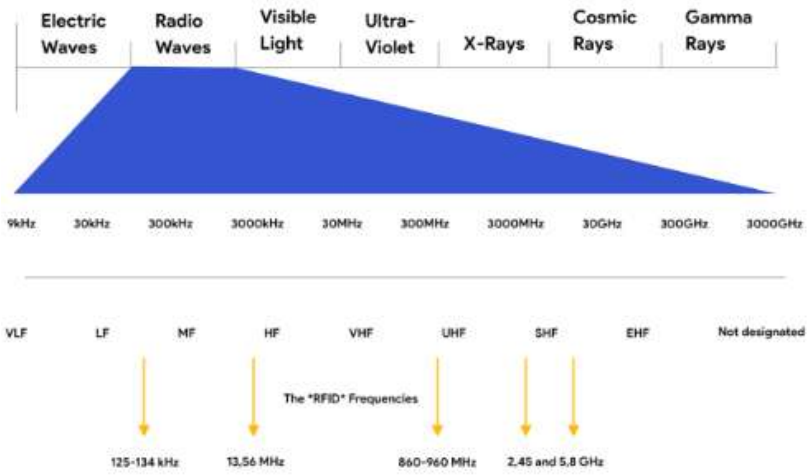

Figure 2.8: Frequency spectrum for RFID systems.

2.7 Coupling types in RFID systems

RFID systems fall into two main coupling categories: far-field coupling, which uses electromagnetic plane waves to communicate and rely on the real power contained in free space, and near-field couplimg, which uses inductive (magnetic) coupling between the transponder tag and the reactive energy circulating the reader antenna [42].

2.7.1 Near-field systems (inductive coupling)

An inductively coupled transceiver, as presented in Figure 2.9, consists of a single microchip and a large-area coil or conductive loop that acts as an antenna. Because these devices are typically passive, the reader must supply the power needed to operate the chip [43]. The antenna coil produces a strong, high-frequency electromagnetic field that propagates around the chip. This field operates as a simple alternating current, and the transceiver's antenna coil, located away from the reader coil, receives only a small amount of this field. After calibration, the voltage generated by the transceiver's antenna coil is used to power the chip.

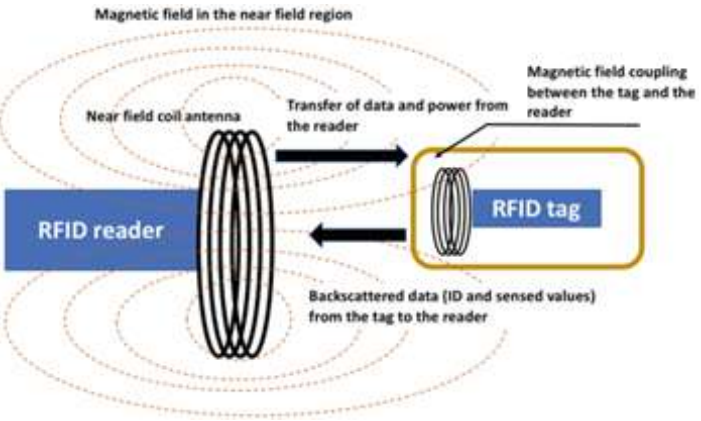

Figure 2.9: Near field coupling.

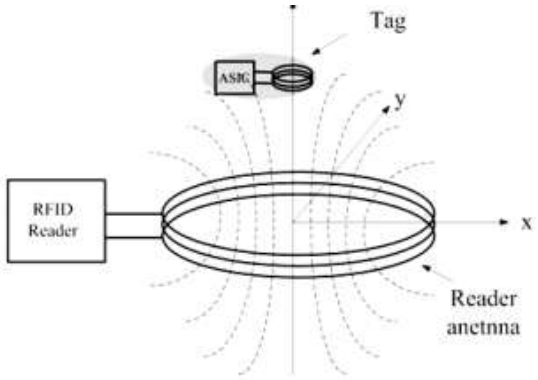

Figure 2.10: Far-field coupling.

2.7.2 Far-field systems

Data sharing in the UHF or SHF range is subject to electromagnetic wave propagation. An electromagnetic wave is produced when a high-frequency signal is applied to the reader antenna. On the other hand, when the card antenna is placed within the electromagnetic field of the reader as shown in the Figure 2.10, an electrical voltage appears at its terminals. This voltage powers the card chip. Passive UHF RFID card antennas come in various forms of radiative coupling. The application is the main factor in selecting an RFID antenna [43].

2.8 Regulations and standards for RFID systems

2.9 Regulations of RFID systems

The regulations governing Radio Frequency Identification (RFID) systems are determined by public authorities. RFID technology is limited to the use of frequency bands allocated for Industrial, Scientific, and Medical applications, known as ISM bands. For RFID systems that use inductive coupling technology, the frequencies 125 kHz and 13.56 MHz are internationally standardized. These frequencies are classified into three separate bands, as shown in Table [17].

2.10 Standards RFID systems

Standards in the field of Radio Frequency Identification (RFID) technology and related industries are somewhat complex, involving a number of bodies and still under development. The International Organization for Standardization (ISO) has issued standards to cover the main areas of RFID applications and uses, namely: air interface standards (for the basic communication between the card and the reader), data content, and encryption [17]. ISO-specific standards for passive UHF RFID are as follows:

- **ISO 18000-6**: Communication protocol.
- **ISO 18047**: Conformance testing.
- **ISO 18046**: Performance evaluation.

Table 2.2: UHF RFID spectrum allocations by region [44].

Region	Frequency range	Authorized Powers
Europe	869.4 to 869.65 MHz	500 mW ERP
	865 to 868 MHz	100 mW ERP-LBT
	865.6 to 867.6 MHz	2 mW ERP-LBT (10 channels of 200 KHz)
	865.6 to 868 MHz	500 mW ERP-LBT
America	902 to 928 MHz	4W EIRP-FHSS (80 channels of 325 KHz)
Asia and Oceania	Japan: 952 to 954 MHz	4W EIRP
	Korea: 908.5 to 914 MHz	4W EIRP
	Australia: 915 to 928 MHz	1W EIRP

2.11 Creative uses for RFID

2.11.1 Animal identification

Animal identification 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 [45].



Figure 2.11: **RFID in Animal Identification.**

2.11.2 Waste Management

RFID can be used for waste management also. RFID tag is attached to each waste bin and every garbage truck has RFID reader attached to it. When waste bin is emptied into truck then reader read tag and transmits data to truck driver cabin wirelessly. At end of route data is transmitted to central server. This data include waste bin number, collected at what time, who was waste collector [45].

2.11.3 Identification

The identification of people, things, or animals is a huge problem [45]. AS an effective identification, the RFID technology consists a good solution. A user has only a single card with embedded RFID chip. This RFID tag number then points to an online database



Figure 2.12: **RFID in Waste Management.**



Figure 2.13: **RFID in National Identification.**

which is accessed by multiple agencies. A single ID card needs to be issued for identification.

2.11.4 Asset Tracking and Locating Objects

RFID can be used to prevent misplacement of items, or to locate items. An asset is tagged with RFID chip for its physical verification. A database is used to keep track of item movements [45].

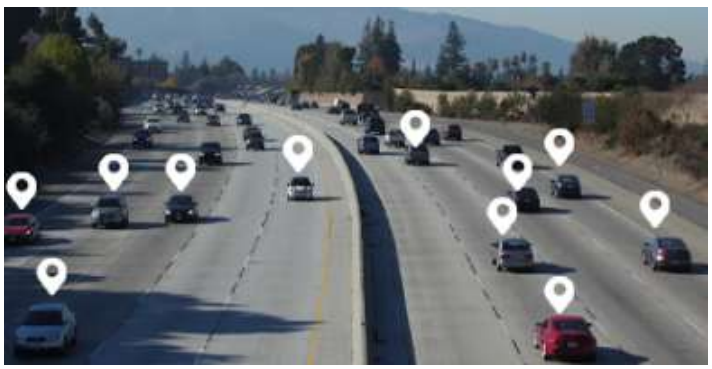

Figure 2.14: **RFID transport system.**

2.11.5 Health care Applications

Health care provides important resources that can contribute significantly to improving patient care. RFID applications can reduce the number of errors by tagging medical items in the healthcare environment, such as patient records, and by tracking medical equipment in a timely manner [45].



Figure 2.15: **RFID in health care.**

2.11.6 Power transfer between antenna and RFID tag chip

When the well-known radio frequency domain condition of impedance matching is achieved, the power transfer between the antenna and the chip is optimal, with 50% of the power effectively transmitted. This means that in the frequency band of interest, the antenna impedance (Z_{ant}) must be equal to the conjugate complex of the chip impedance (Z_{Chip}) [12, 46].

$$Z_{ant} = Z^*_{chip} \tag{2.1}$$

where Z_{ant} is the antenna input impedance, and Z^*_{chip} is the chip impedance.

2.12 Passive UHF RFID system

Passive UHF RFID systems mainly consist of three types of components, i.e., readers, tags, and end application, for example, database. The reader is essentially a transceiver operating at UHFs, and it is used to communicate with tags and with the end user application. An RFID tag contains an antenna and an IC. The IC of the tag has an internal memory containing a unique electronic product code (EPC), which is used for identification purposes [47].

2.12.1 Energy and information transfer between reader and Tag

In response to reader commands, the tag adjusts its signals according to strict regulations, especially in Europe according to the ETSI 302 208 standard. The reader is allowed to operate at a maximum power of 2 watts ERP (i.e., 3.2 watts EIRP) and must use the LBT (Listen Before Talk) feature to detect other signals in the band before transmitting [47].

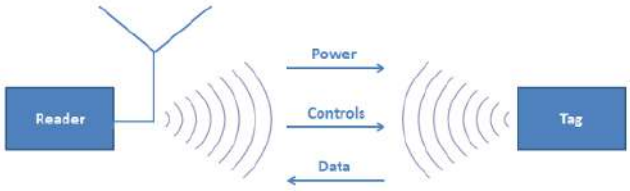

Figure 2.16: An illustration of a passive UHF RFID system.

2.13 Advantages of using an RFID systems

RFID has several benefits that make it useful for identifying applications, even though it is unlikely to fully replace conventional barcodes very soon. These benefits include [48]:

- **Flexible tag positioning:** Tag placement is less restricted because there is no need for line-of-sight .
- **Read/Write capabilities:** RFID tags have a larger read range than, barcodes, RFID tags may hold a lot of data in addition to a unique identification.
- **Lower inventory costs:** Reduces inventory control and provision in costs.
- **Its ability to identify items individually rather than generically**.
- RFID tags can be combined with sensors.

2.14 Limitations of RFID technology

We summary here the RFID technology drawbacks and restrictions [48]:

- **Cost:** Prices of active or semi-passive tags are even more of a hindrance, allowing their economic application only for scanning high-value goods over long ranges.
- **Standardization:** While the characteristics of the program and the usage scenario determine the appropriate tag, differences in standards and the amount of information lead to data incompatibility and conflict management.
- **Frequency issues:** The optimal frequency selection depends on the transmission method, the behavior of the tagged goods, and the surrounding environment.
- **Faulty manufacture of tags**: Currently, tag manufacturing is not completely error-free.
- **Quick technology obsolescence:** RFID technology is undergoing rapid development and is becoming less effective compared to previous technologies.

2.15 Conclusion

This chapter has provides an overview of RFID fundamentals, covering both the tag and the reader and outlining their key features. Additionally, we have presented their applications, including in the medical field. Use cases such as tracking and tagging individuals, and contactless metro entry via pre-paid electronic tickets, demonstrate how RFID serves as a practical identification technology. The chapter also discusses passive UHF RFID.

Chapter 3

Circularly polarized RFID reader antenna for UHF/SHF applications

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3.1 Introduction

In this chapter, we design and simulate a dual-band circularly polarized (CP) antenna for RFID portable applications. The proposed reader antenna works concurrently as an RFID scanner at 0.915 GHz and 2.45 GHz. The frequency-selective surface (FSS) reflector is used to enhance radiation characteristics. The CST Microwave Studio software is used for antenna design.

3.2 CST Microwave Studio Software

CST Studio Suite is a high-performance 3D electromagnetic analysis software developed by Dassault Systems, designed to handle the full electromagnetic spectrum from static fields up to optical frequencies. Its electromagnetic field solvers cover applications across the EM spectrum within a single user interface, and can be coupled together to perform hybrid simulations. The suite offers solution methods in both time domain and frequency domain, with FIT and TLM as time-domain methods particularly well-suited for broadband, antenna, and complex applications. Common subjects of analysis include the performance and efficiency of antennas and filters, electromagnetic compatibility and interference, and thermal effects in high-power devices [49].

3.3 Design process of the proposed reader antenna

First, we design a circularly polarized RFID reader antenna using an FSS reflector for UHF (0.915 GHz) and SHF (2.45 GHZ) frequencies. Figure 3.1 shows a brief overview of the design process steps.

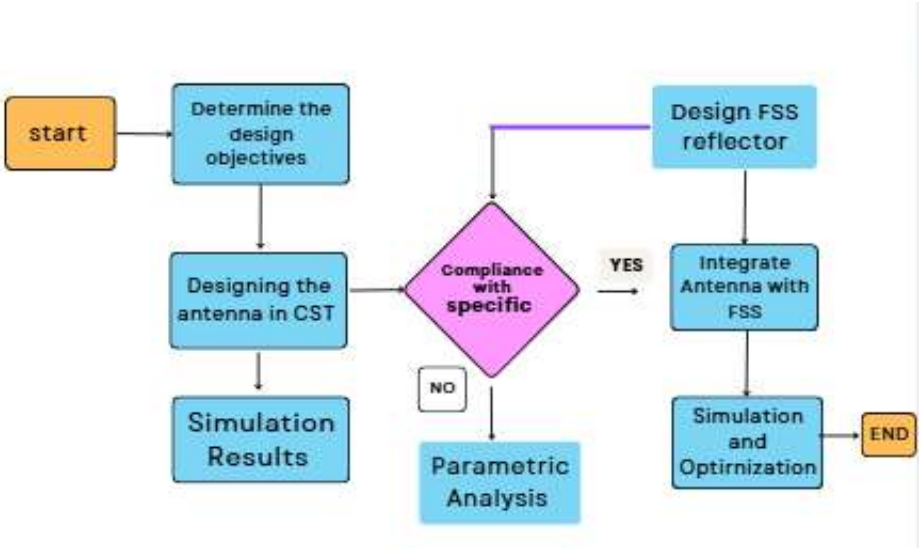


Figure 3.1: Schematic diagram of the antenna design steps.

3.4 Antenna design

Figure 3.2 illustrates the geometry of the proposed antenna, inspired by an antenna structure developed in [50]. The design is implemented on a 1.6 mm thick FR4 substrate, with a relative permittivity of $\varepsilon_r = 4.4$ and a dielectric loss tangent of $\tan\delta = 0.02$. The overall dimensions of the antenna are 85 x 85 x 1.6 mm³. Each pair of crossed dipoles consists of perpendicularly positioned elements, with parameters including the band widths W 2 and W 3 and the arrowhead path lengths L1, L3, L4, and L 2. The crossed dipoles are also composed of rectangular patches, with geometric parameters related to the patch length and width L6, L6, W4, and W5, respectively. The distance between the two pairs of crossed dipoles is denoted as S1 and S2. Crossed dipoles were formed on the top and bottom surfaces of the substrate, consisting of a pair of dipoles centrally fed via a 50 Ω coaxial cable. The proposed feeding mechanism can provide a phase difference of 90° between the arms of the crossed dipoles for both the 0.915 GHz and 2.45 GHz bands.

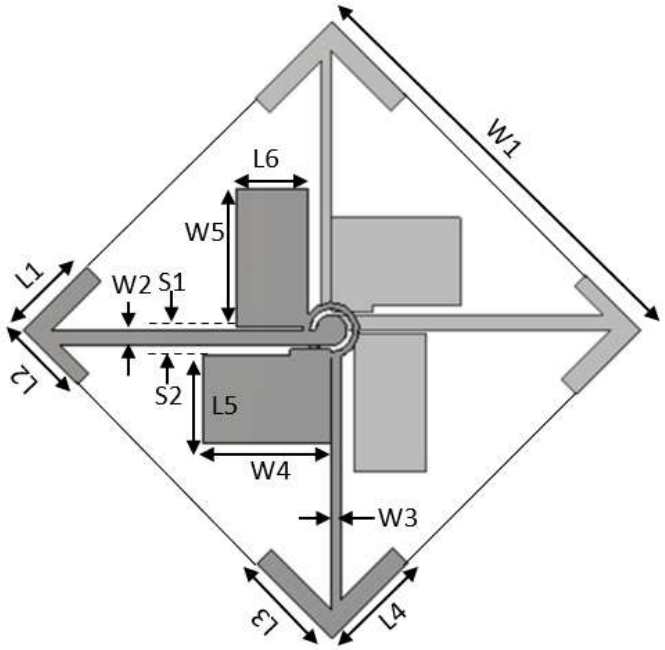


Figure 3.2: Proposed reader antenna design.

Table 3.1: Dimensions of the optimized antenna.

Parameter	W_5	W_1	L_1	L_2	L_3	L_4	L_5	L_6	W_2	W_3	W_4	S1	S2
Value (mm)	27	85	17.5	15	17	21	17	14	3	2	25	0.6	1.9

3.4.1 Parametric study

3.4.1.1 Reflection coefficient

Figure 3.3 shows the curves of the reflection coefficient $|S_{11}|$ as a function of frequency of the proposed RFID reader antenna for different values of L6. The length L6 is a key factor

for achieving improved matching.

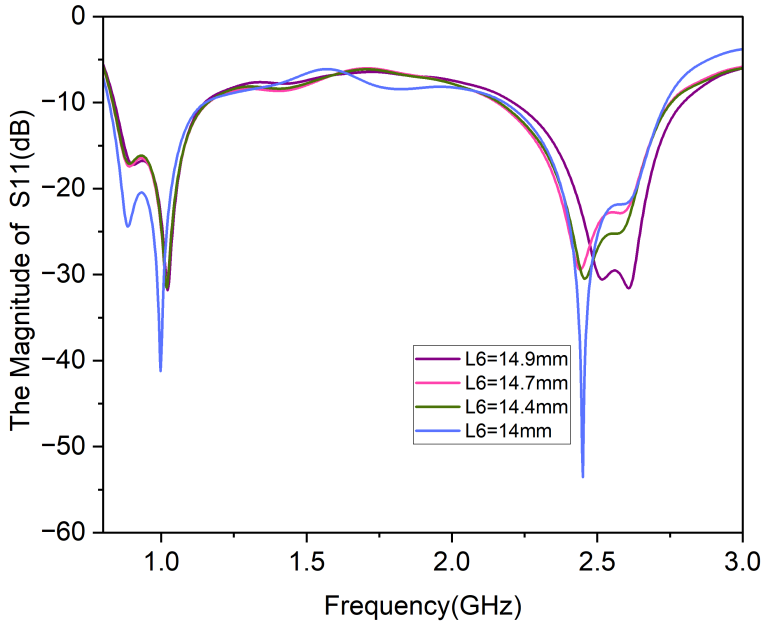


Figure 3.3: Value of $|S_{11}|$ in dB versus frequency in GHz of the proposed antenna.

3.4.1.2 Axial ratio

Figure 3.4 shows the change in axial ratio (AR in dB) as a function of frequency (in GHz) for different values of W4 = 25. We note that W4 affects the polarization performance, as the lowest values of axial ratio occur at 0.915 GHz and 2.45 GHz, indicating the achievement of circular polarization.

3.4.2 Finalized reader antenna

3.4.2.1 Reflection coefficient

Figure 3.5 shows the simulation results for the antenna reflection coefficient $|S_{11}|$. The antenna impedance is matched across the UHF and SHF frequency bands, with a reflection coefficient estimated at -10 dB. At 0.915 GHz, a lower value of -21.18 dB is obtained, while at 2.45 GHz a value of -53.54 dB is achieved. This good matching indicates high antenna efficiency.

3.4.2.2 Axial ratio

Figure 3.6 illustrates the axial ratio (dB) versus frequency of the proposed antenna. At a resonant frequency of 0.915 GHz, the axial ratio is equal to 2.19 dB (lower than 3 dB). At 2.45 GHz, the AR is equal to 1.93 dB, indicating that the antenna radiates a circularly polarized field.

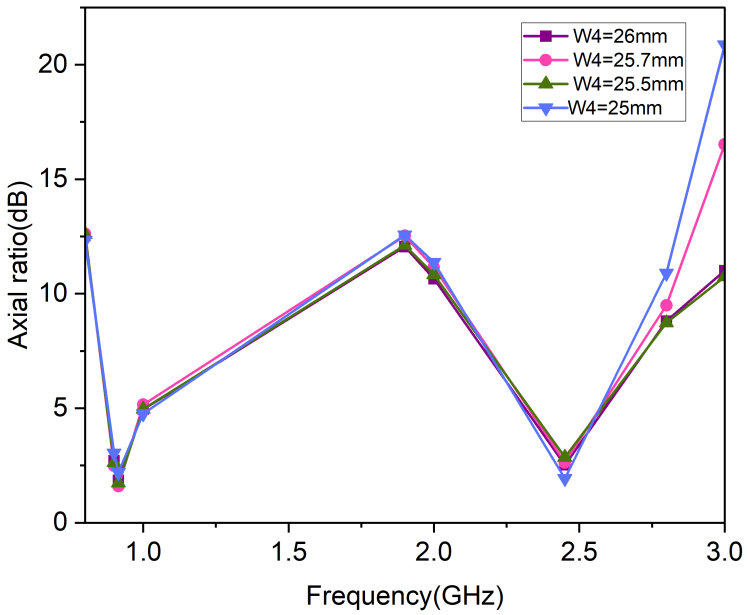


Figure 3.4: Axial ratio in dB versus frequency in GHz for the proposed antenna.

3.4.2.3 Electric field

Figures 3.8 and 3.9 present the radiated field at 0.915 GHz and 2.45 GHz at various instances include 0° (figs.3.8a and 3.9a), 90° (Figs. 3.8b and 3.9b), $\omega t = 180°$ (Figs. 3.8c and 3.9c), and $\omega t = 270°$ (Figs. 3.8d and 3.9d). The electric field rotates in RHCP toward $z > 0$, while the LHCP electric field is in $z < 0$. Figures 3.24a and 3.24b represent the surface current on the reader antenna surface at 0.915 GHz and 2.45 GHz, respectively, where the substrate current goes to zero due to its low conductivity.

3.4.2.4 Realized gain and efficiency

A graph of the gain and efficiency values attained by the suggested antenna within a certain frequency range is displayed in Figure 3.10 and 3.11. It is evident that the antenna's efficiency and gain are closely correlated.this relationship may be described by the previously given equation.

At 0.915 GHz and 2.45 GHz, the gain levels are 1.87 dB and 1.52 dB, respectively, the efficiency levels are about 95% and 88% respectively.

3.4.2.5 Radiation Pattern

As presented in Figure 3.12, the proposed antenna exhibits directional radiation at both 0.915 GHz and 2.45 GHz.

Figure 3.13 depicts the radiation pattern in polar representation of the proposed antenna. The maximum bidirectional radiation at frequencies of 0.915 GHz and 2.45 GHz is plotted for $\varphi = 0°$ at the (x-z plane) and $\varphi = 90°$ (y-z plane).

Figure 3.7 shows the distribution of the surface current on the top of the reader antenna at frequencies of 0.915 GHz and 2.45 GHz. The longer monopoles resonate at 0.915 GHz, while the shorter monopoles resonate at 2.45 GHz.

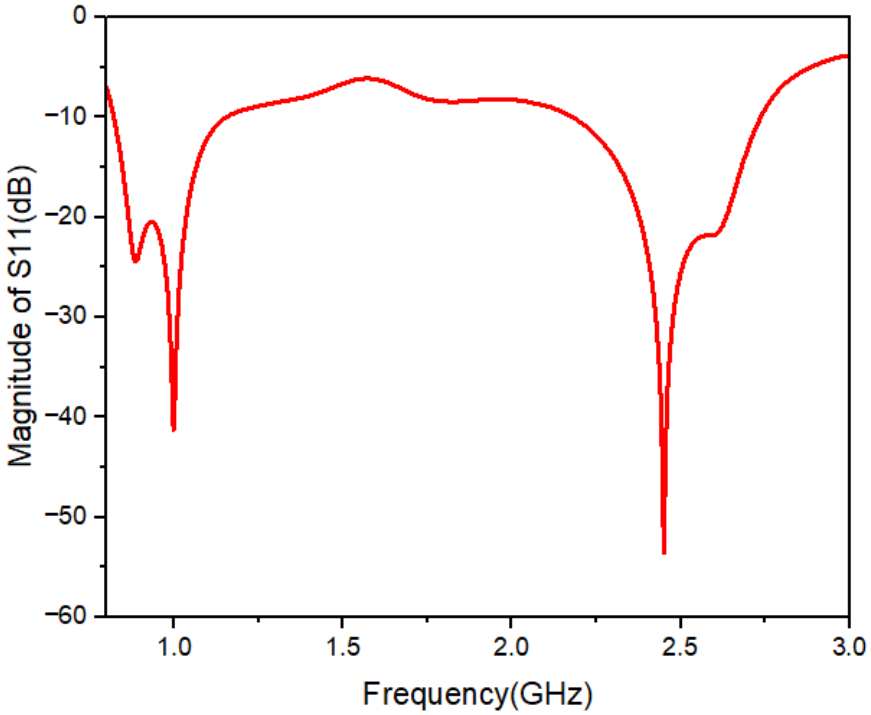


Figure 3.5: Antenna reflection coefficient $|S_{11}|$ (dB) versus frequency (GHz) of the proposed reader.

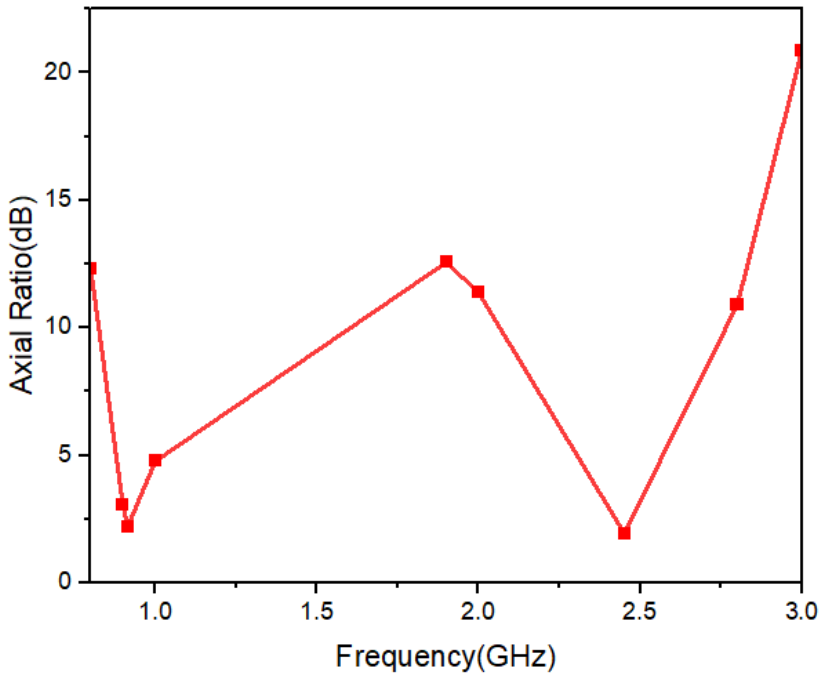
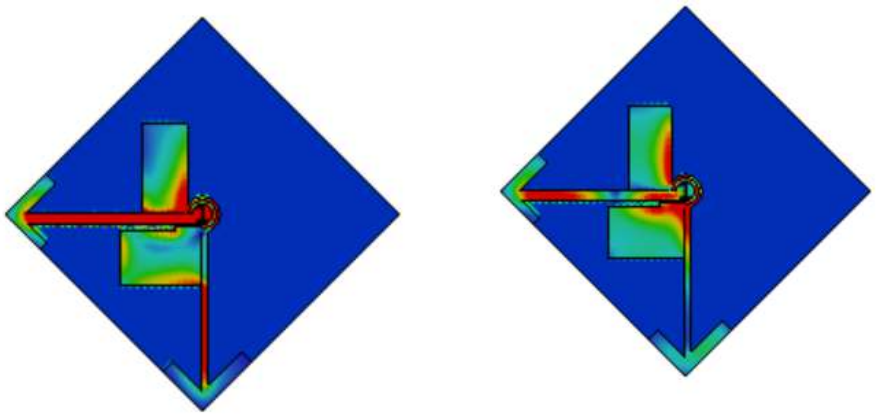
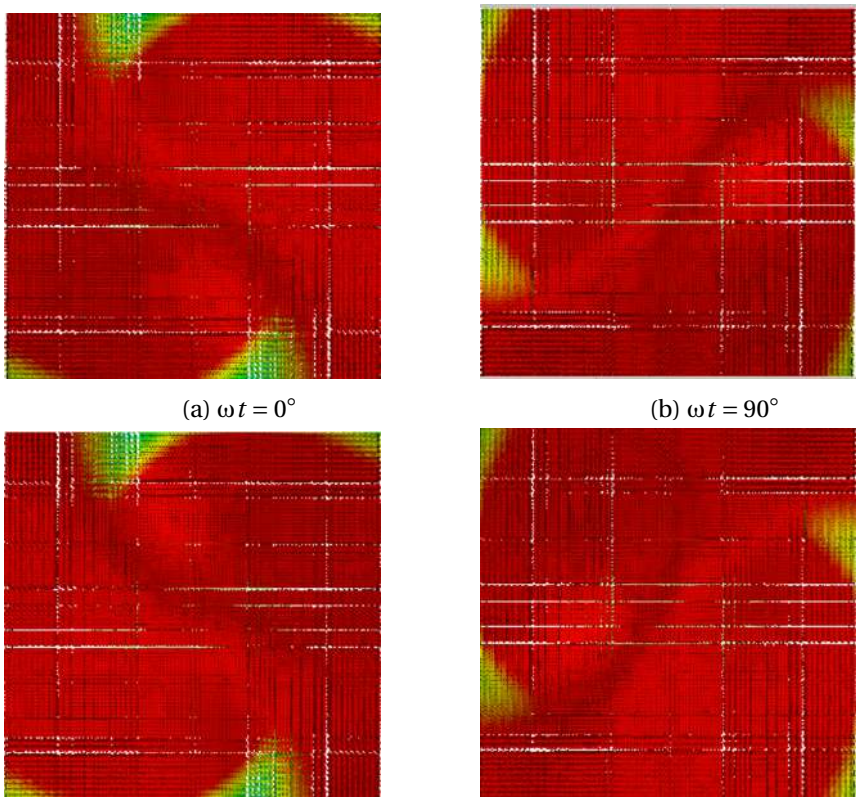


Figure 3.6: Axial ratio in dB against frequency in GHz for the proposed antenna.



(a) 0.915 GHz (b) 2.45 GHz

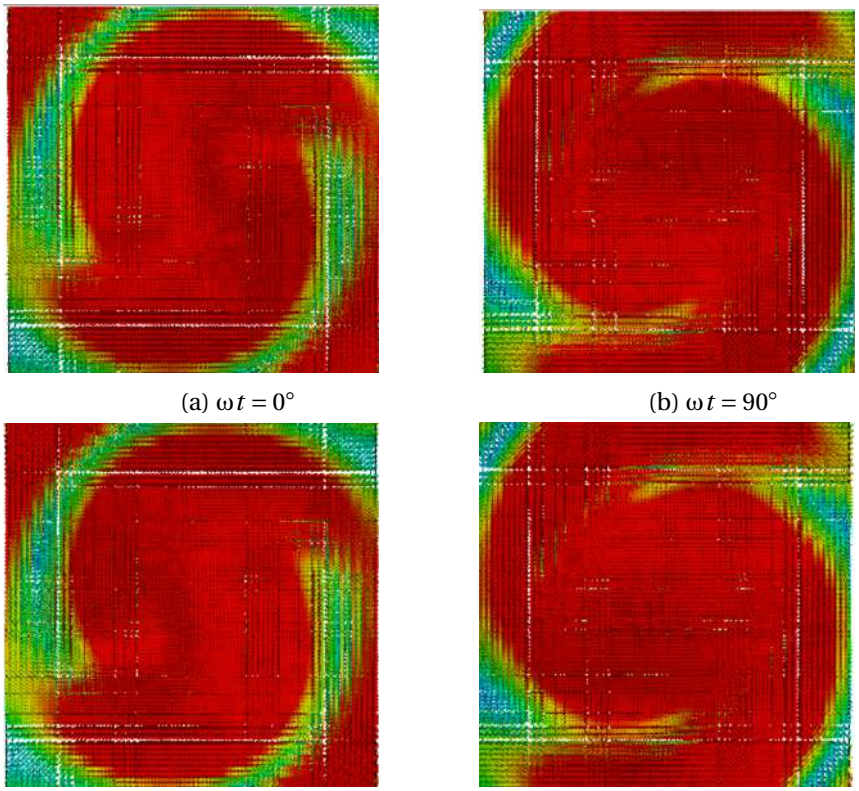
Figure 3.7: Surface currents at 0.915 GHz and 2.45 GHz of the proposed antenna.



(a) $\omega t = 0^\circ$ (b) $\omega t = 90^\circ$

(c) $\omega t = 180^\circ$ (d) $\omega t = 270^\circ$

Figure 3.8: Radiated electric field at various instances of antenna at 0.915 GHz.



(a) $\omega t = 0°$ (b) $\omega t = 90°$

(c) $\omega t = 180°$ (d) $\omega t = 270°$

Figure 3.9: Radiated electric field at various instances of antenna at 2.45 GHz.

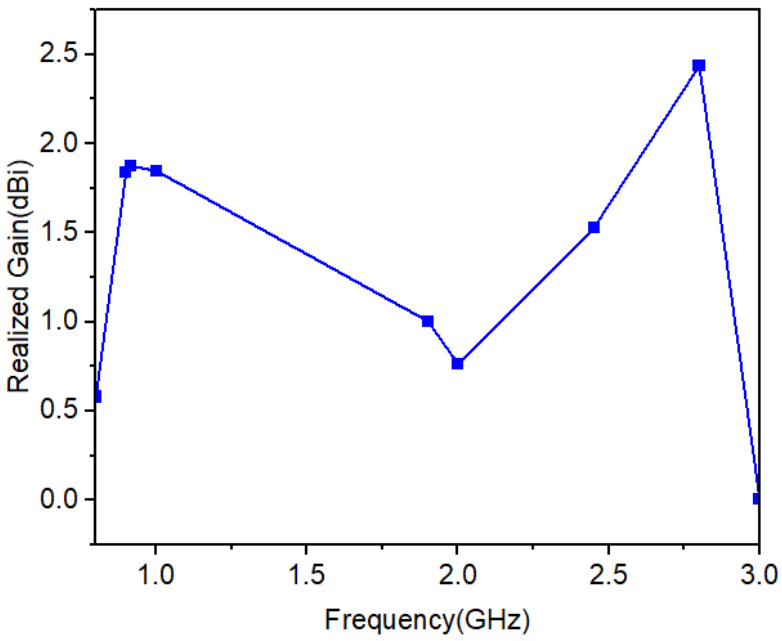


Figure 3.10: Realized gain against frequency of the proposed antenna.

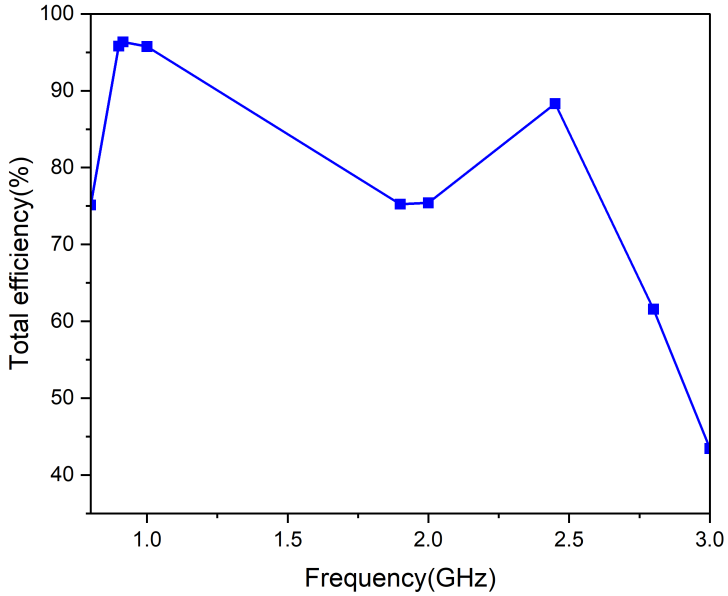
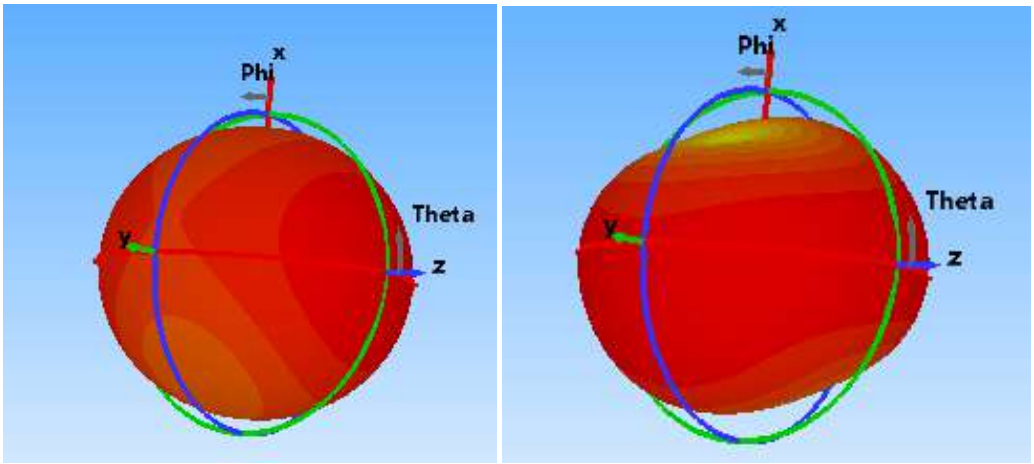
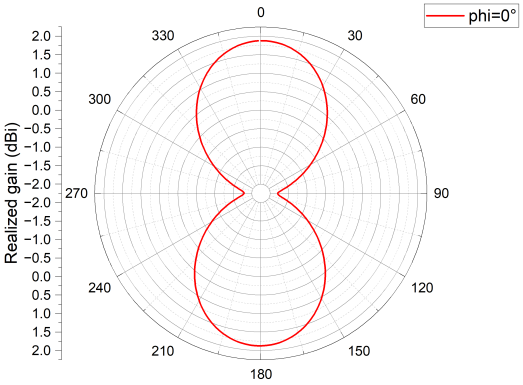


Figure 3.11: efficiency gain against frequency of the proposed antenna.

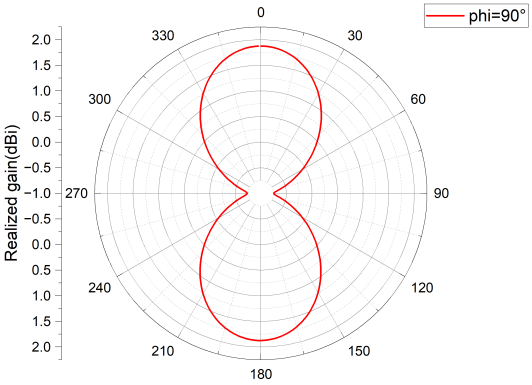


(a) (b)

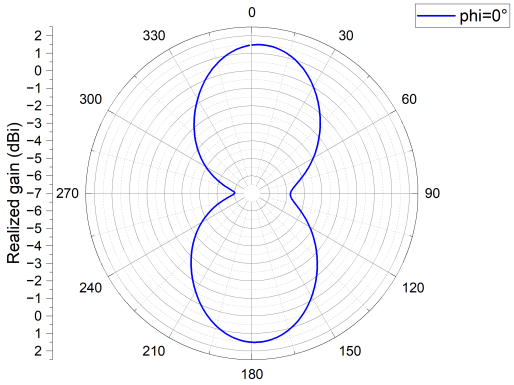
Figure 3.12: 3D radiation patterns, (a) at 0.915 GHz; (b) at 2.45 GHz.



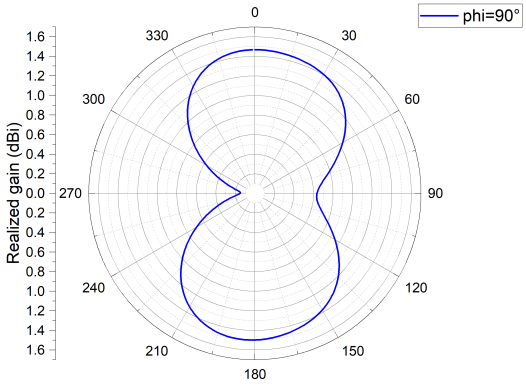
(a) $\varphi = 0°$ at 0.915 GHz.



(b) $\varphi = 90°$ at 0.915 GHz.



(c) $\varphi = 0°$ at 2.4 GHz.



(d) $\varphi = 90°$ at 2.4 GHz.

Figure 3.13: Radiation patterns of antenna at 0.915 GHz and 2.4 GHz.

3.5 FSS unit cell design

The proposed antenna and the proposed FSS unit cell are intended to function in the same frequency ranges. It must thus have a bandwidth that is either larger than or equal to the antenna bandwidth. As presented in Figure 3.14, the proposed FSS unit cell consists of a square loop with cross at the middle.

Actually, it can offer increased bandwidth, reduced dimensions needed for the appropriate frequency bands, and improved angular resolution. The structure proportions are intended to encompass the antenna bandwidth while enabling operation at the same frequencies. To use CST to construct the structure depicted.

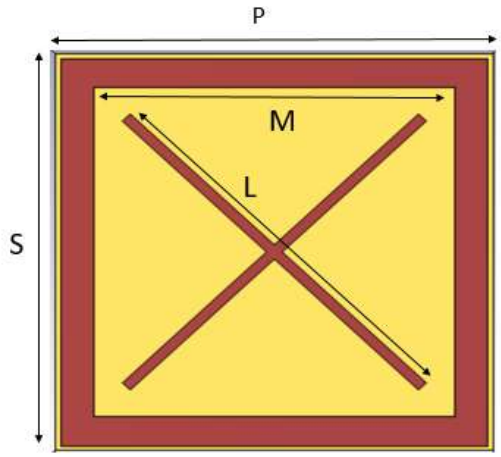


Figure 3.14: Proposed FSS unit cell.

Table 3.2: displays the optimized dimensions of the proposed FSS unit cell.

Table 3.2: Dimensions of the proposed FSS unit cell.

Parameter	P	S	L	M
Value (mm)	50.20	50.20	46.7	41.60

Figure 3.15 shows the reflection and transmission coefficients (S_{11} and S_{21}) as a function of frequency of the proposed FSS unit cell. The transmission coefficient is -37.29 dB at 0.915 GHz and -35.37 dB at 2.45 GHz, which means that a high reflection occurs due to the FSS reflector at 0.915 GHz and 2.45 GHz. The transmission coefficient is -0.38dB at 1.6 GHz,meaning that approximately 99%. The transmission coefficient is-0.031 dB at 1.467 GHz, which means that about 99.28%. of the power of the meaning incident waves is transmitted.

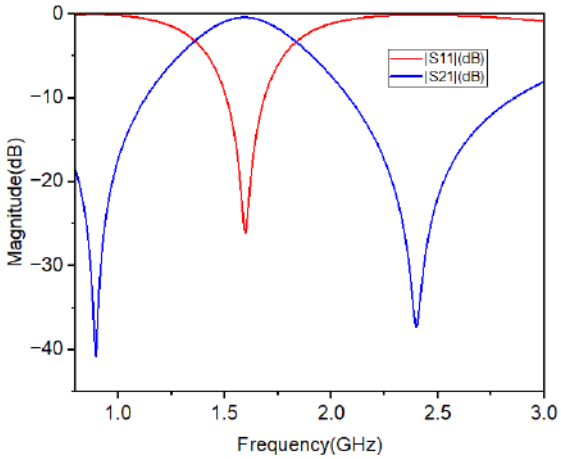


Figure 3.15: Transmission and reflection coefficients as a function of frequency of the proposed FSS unit cell.

3.6 Antenna over FSS reflector

The proposed antenna performance can be improved by integrating it with an FSS reflector. Antenna performance enhancement is significantly influenced by the size of the FSS and the height of the air gap between the antenna and FSS reflector. The enhanced parameter is the gain as expected, extending the reading range of the reader antenna.

3.6.1 FSS size effect on antenna performance

In order to understand how the size of the FSS reflector influences the overall antenna performance, we tested the antenna by combining it with three different FSS array configurations, namely 4×4, 5×5, and 6×6, when there was a 75 mm air gap between the antenna and the FSS.

Figure 3.16 shows the evolution of the reflection coefficient magnitude, $|S_{11}|$, with a change in the size of the FSS array. The first resonance at 0.915 GHz remains almost constant regardless of the array size, while the second resonance at 2.45 GHz shifts slightly towards lower frequencies.

Figure 3.17 illustrates the change in gain achieved by varying the size of the frequency-selective filter (FSS). The results show that with an increasing number of base cells, the gain improves within the target operating ranges. An appropriate FSS architecture must be selected to achieve optimal performance. The effect of FSS size on the realized gain is reported in Table 3.3.

Table 3.3: Effect of the FSS size on realized gain.

Configuration	Gain (dBi) at 0.915 GHz	Gain (dBi) at 2.45 GHz
Antenna alone	1.87	1.52
Antenna with FSS (4 × 4)	6.83	6.15
Antenna with FSS (5 × 5)	8.14	5.80
Antenna with FSS (6 × 6)	8.26	5.70

Based on the results obtained and considering the size of the antenna in relation to the number of cells in the FSS unit, the 5×5 array is the best in terms of antenna performance.

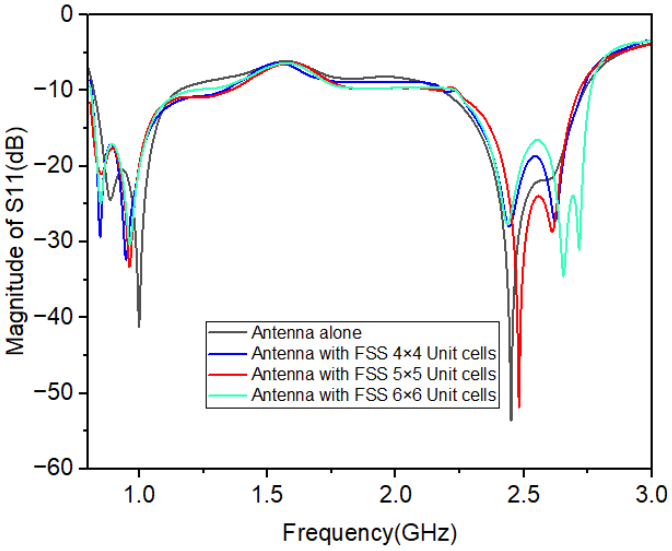


Figure 3.16: Reflection coefficient of the proposed antenna with FSS size change.

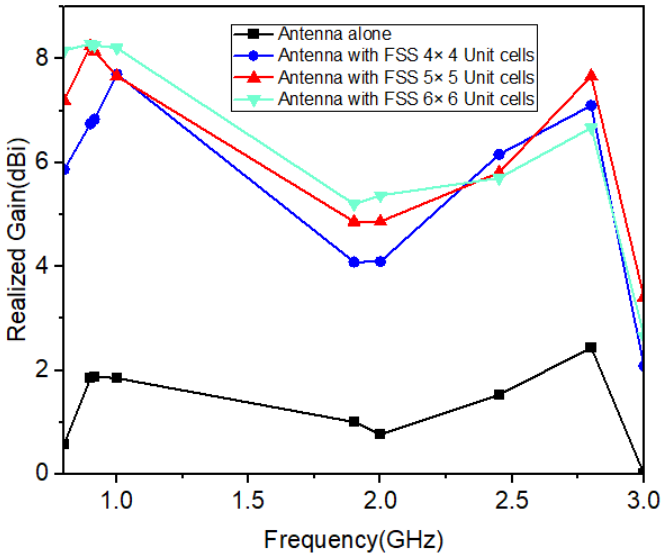


Figure 3.17: Realized gain with changes in the FSS size.

3.6.2 Influence of the air gap on antenna performance

In this section, we investigate the influence of the air-gap height HG on the antenna performance by integrating the antenna with a 5×5 FSS array, which was identified as the optimal configuration based on the results obtained in the previous analysis. The air-gap distance between the antenna and the FSS surface is then varied in order to determine the value that yields the best overall performance.

Figure 3.18 presents the geometry of the proposed antenna integrated with the 5×5 FSS unit cells array.

Figure 3.19 shows that the height of the air gap (HG) acts as a selective adjustment coefficient; without affecting the stability of the frequency band. Based on the results, the value of HG=85 mm is technically ideal, as it achieved the best impedance matching while maintaining stable performance of the antenna baseband.

Figure 3.21 shows the evolution of the achieved gain in decibels with varying air gap values. The gain reaches its maximum value at both 0.915 GHz and 2.45 GHz, at 7.86 and 8.32 GHz respectively, when the air gap is 85 mm. This indicates the reflection and forward direction of the electromagnetic waves.

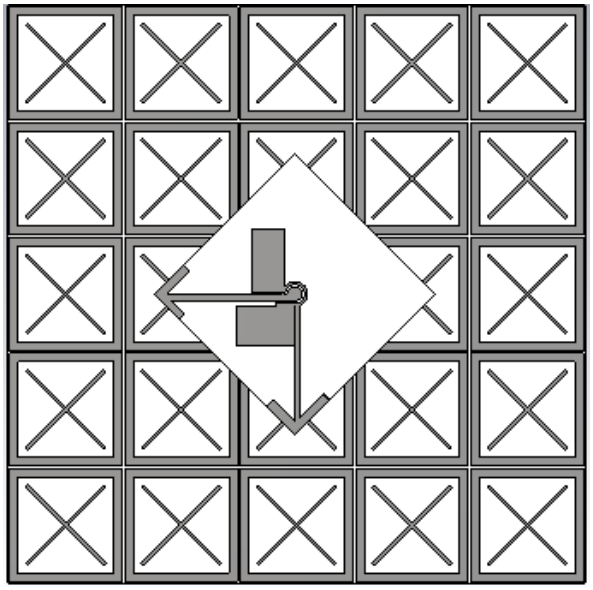


Figure 3.18: Configuration of proposed antenna integrated with 5 × 5 FSS unit cells array.

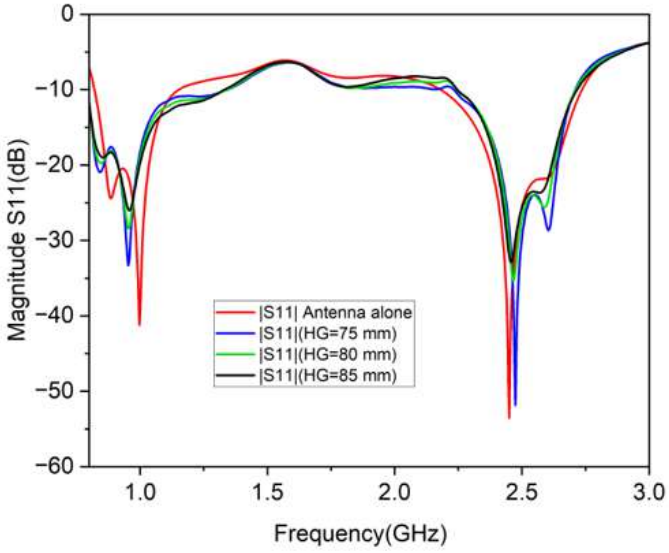


Figure 3.19: Reflectance coefficient with a variation in the air-gap height.

The axial ratio values with changes in air gap height are shown in Figure 3.20. At frequencies of 0.915 GHz and 2.45 GHz, respectively, the antenna without a frequency-selective surface exhibits low axial ratios of 2.19 dB and 1.93 dB. In contrast, the axial ratio changes with air gap values when a frequency-selective surface is used. The optimal air gap height is 85 mm, producing a circularly polarized beam in the second band with an axis ratio of 1.61 dB. Figure 3.22 shows how the antenna overall efficiency varies with frequency as the air gap changes. The efficiency value is 95% at 0.915 GHz and 86% at 2.45 GHz with a gap height of 85 mm.

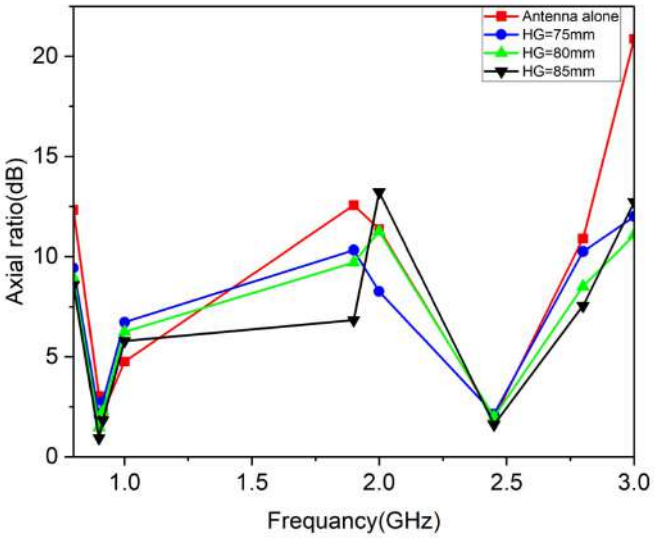


Figure 3.20: Axial ratio values versus frequency for different values of air-gap HG.

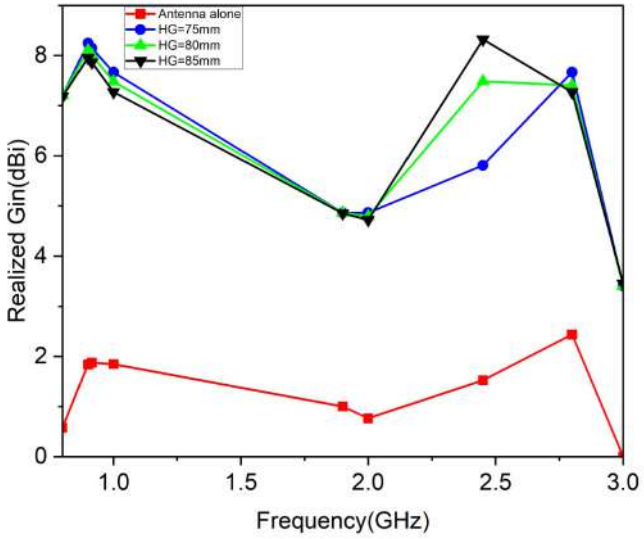


Figure 3.21: Antenna gain values versus frequency for different values of air-gap HG.

The evolution of directivity with changes in air-gap values is seen in Figure 3.23. The direction value rises as the air-gap widens; the highest observed value is at HG=85 mm, with a directivity value of 8.07 dBi at 0.915 GHz and 8.95 dBi at 2.45 GHz. The ideal frequency for improving antenna directional capabilities is 2.45 GHz.

Figure 3.25 presents the radiation patterns of the proposed reader antenna alone and the proposed antenna over FSS reflector. The realized gain is considerably enhanced in the broadside direction by an amount of 5.99 dBi at 0.915 GHz and 6.8 dBi at 2.45 GHz. Figure 3.24 shows the surface current distribution of the proposed antenna over FSS reflector at 0.915 GHz and 2.45 GHz, where the surface current is highly concentrated at the center while the surrounding FSS cells show near-zero levels, confirming the FSS en-

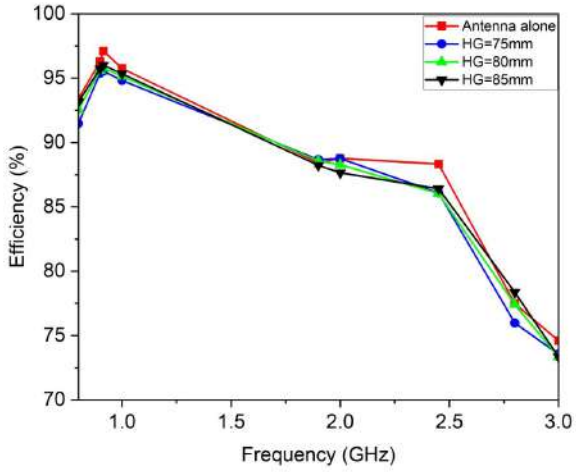


Figure 3.22: Total efficiency values versus frequency with changes in air-gap values.

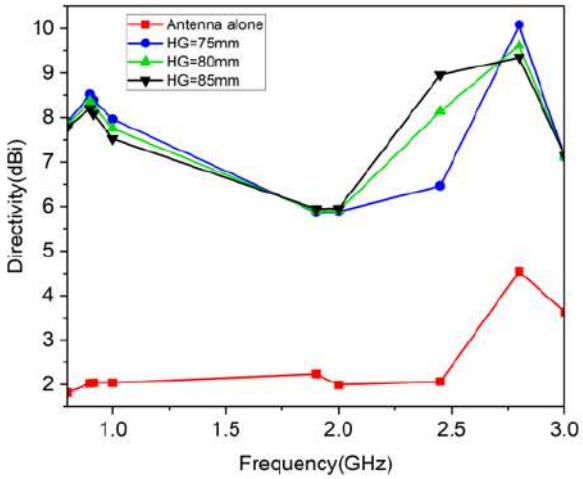
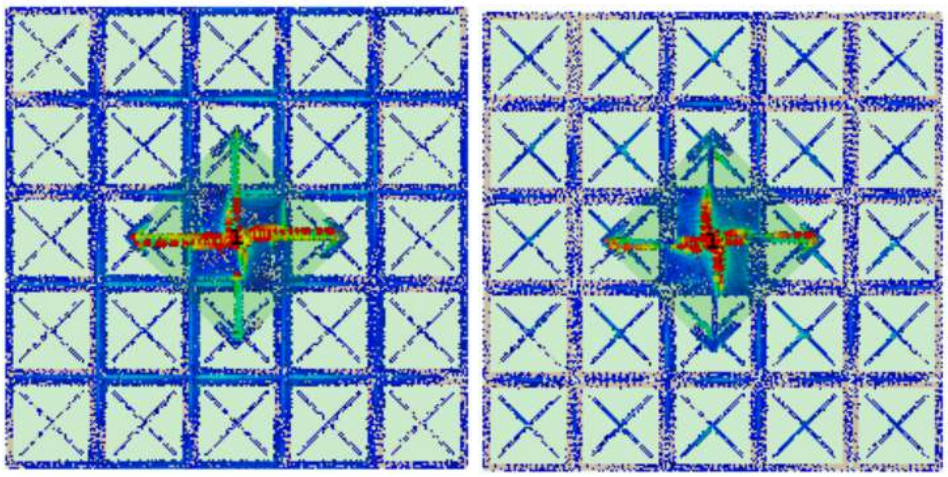


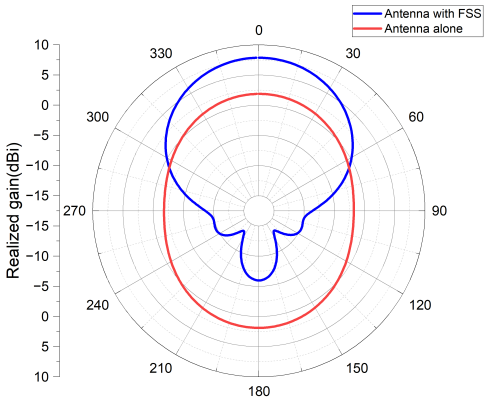
Figure 3.23: Directivity evolution versus air-gap values change.

hancement of the antenna performance at both operating frequencies.

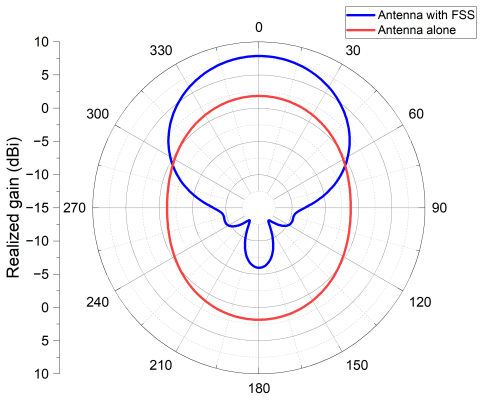


(a) 0.915 GHz (b) 2.45 GHz

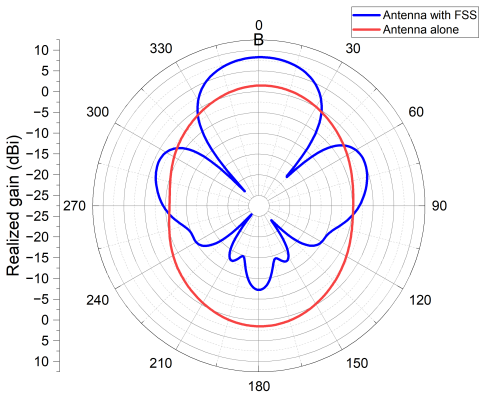
Figure 3.24: Surface currents at 0.915 GHz and 2.45 GHz of the proposed antenna over FSS.



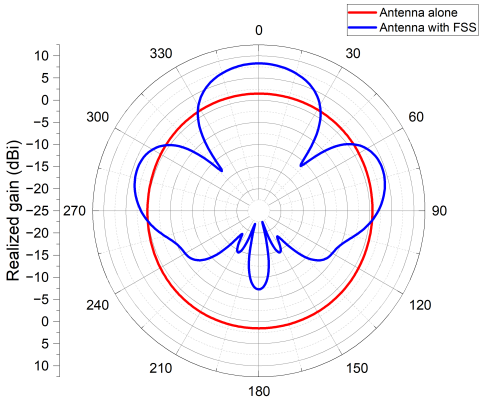
(a) φ = 0° at 0.915 GHz.



(b) φ = 90° at 0.915 GHz.



(c) φ = 0° at 2.4 GHz.



(d) φ = 90° at 2.4 GHz.

Figure 3.25: Radiation patterns of the proposed antenna alone and over FSS reflector at 0.915 GHz and 2.4 GHz.

3.7 Performance comparison with the literature

Table 3.4 compares the proposed antenna with previous work [31, 50–53] based on the following criteria: size, bandwidth, polarization, and gain. This comparison shows that the proposed antenna achieves a high gain of 7.86 dB at 0.915 GHz and 8.32 dB at 2.45 GHz when using an FSS reflector, compared to other antennas [31, 50–53]. Despite its small size of $85 \times 85 \times 1.6$ mm^3, it exhibits consistent performance in terms of circular polarization for both the UHF and SHF bands with or without the FSS reflector. Achieving a small size with enhanced performance increases the usability of this antenna in modern RFID applications, where it operates efficiently within the UHF and SHF bands.

Table 3.4: Comparison of proposed antenna performance with literature.

Ref., year	Size (mm^3)	Bandwidth (GHz)	Field Pol.	Gain (dBi)
[51], 2019	41 × 100 × 1.6	0.88-0.96 / 2.28-2.57	LP	4.37
[50], 2020	85×85×1.6	0.882-0.936 / 2.35-2.58	CP	1.4 / 3.1
[52], 2021	104×104× 1.524	0.840-0.960 / 2.4-2.48	CP	0.8 / 4.6
[31], 2024	120×140× 0.817	0.881-0.942 / 2.32-2.52	CP	-1.26 / 3.26
[53], 2025	140×140× 1.524	0.866-1.05/ 2.25-3.13	CP	1.73/ 5.7
Antenna alone	85.0×85.0×1.6	0.821-1.157/ 2.20-2.74	CP	1.87/ 1.52
Antenna over FSS	251×251×86.6	0.821-1.157/ 2.20-2.73	CP	7.86/ 8.32

3.8 Conclusion

This chapter has presented the design and simulation of an RFID reader antenna adapted operating within UHF/SHF applications. Various parameters have been presented and studied to understand the operation mechanism of the proposed antenna. The simulated results have shown that the antenna achieves a high gain of up to 7.86 dBic at 0.915 GHz and 8.32 dBic at 2.45 GHz. The antenna without the FSS has provided bidirectional circularly polarized radiation, while integrating the FSS surface contributed to improving the forward radiation characteristics. Thus, this solution is simple and cost-effective, making it suitable for handheld RFID applications, where the compact size and the long range is required.

General Conclusion

In this work, a dual-band circularly polarized (CP) antenna operating at 0.915 GHz and 2.45 GHz has been designed for RFID applications. A frequency-selective surface (FSS) reflector has been integrated to improve the radiation characteristics. The study involved the analysis and evaluation of several configurations, ultimately leading to the selection of the most suitable design using CST simulation software. The simulated results have demonstrated satisfactory agreement with the required performance specifications.

In the first chapter, we presented the RFID systems by outlining their concepts, components, and classifications. Furthermore, we explained how they operate by outlining several standards, regulations, and their applications. We concluded the chapter with the benefits and limitations of RFID systems.

In the second chapter, RFID technology was introduced, explaining its basic components and various classifications. The principle of its operation was also explained in a simplified manner, in addition to presenting the main laws and standards that govern its use. We have also addressed the most prominent fields of application for this technology in several areas. Finally, the main advantages have been summarized, with reference to some related limitations and constraints.

The third chapter has included the simulation results for a dual-band circularly polarized reader antenna designed for RFID applications, operating at 0.915 GHz and 2.45 GHz. The antenna uses a frequency-selective surface (FSS) as a reflector for radiation enhancement. All simulations were carried out using CST Microwave Studio. Starting from an initial design inspired by the literature, a series of incremental modifications were introduced to enhance performance. After several design iterations, the final antenna geometry has been obtained, with compact dimensions of $85 \times 85 \times 1.6\ mm^3$, fully meeting the application requirements. Following the initial antenna design, an FSS reflector has been integrated, and a parametric study has been carried out to assess the impact of the array size, examining 4×4, 5×5, and 6×6 cell configurations, as well as the air gap distance separating the antenna and the FSS. The optimal setup was found to be a 5×5 FSS array positioned at a distance of 85 mm from the antenna. This configuration yielded significant gain improvements, reaching 7.86 dBi at 0.915 GHz and 8.32 dBi at 2.45 GHz. Consequently, the proposed antenna proves its outstanding ability to combine dual-band operation with circularly polarized radiation, achieving high radiation efficiency and gain enhancement. This makes it an ideal candidate for a dual band modern RFID system applications, requiring long reading distances. As a future direction for this work, we will design tags operating at both 0.915 GHz and 2.45 GHz to complete the overall system.

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