

FIELD : SCIENCE AND TECHNOLOGY FACULTY OF TECHNOLOGY
MAJOR : ELECTRONICS ELECTRONICS DEPARTMENT
OPTION : TELECOMMUNICATION N°:



Academic Year : 2025/2026

"قَالُوا سُبْحَانَكَ لَا عِلْمَ لَنَا إِلَّا مَا عَلَّمْتَنَا
إِنَّكَ أَنْتَ الْعَلِيمُ الْحَكِيمُ"

(صدق الله العظيم)

الآية 32 من سورة البقرة

Acknowledgements

First and foremost, I would like to thank Almighty allah for granting me the courage, patience, and good health necessary to accomplish this modest work.

I would like to express my sincere gratitude to my supervisor, **Pr. Fadila BENMEDDOUR**, for accepting to supervise this work, for her continuous support and guidance, and for her valuable comments and advice throughout the course of this project.

My heartfelt appreciation also goes to the honorable members of the jury : Dr. ZERDOUMI Zohra and Dr. ZEMOURI Nahed for accepting to evaluate this work.

Finally, I would like to express my deepest gratitude to my parents. Any success I achieve is the result of their years of sacrifice, support, and education.

Thanks.

Table of Contents

Table of Contents.....	II
List of Figures.....	V
List of Tables.....	VII
Abstract.....	IX
Résumé.....	IX
Arabic Summary.....	IX
General Introduction.....	1
Bibliographie.....	60

CHAPTER 1

1.1. Introduction.....	6
1.2. Definition of Patch Antenna.....	6
1.3. Structure of a Printed Antenna.....	7
◇ 1.3. 1. Radiating Patch.....	7
◇ 1.3. 2. Dielectric Substrate.....	7
◇ 1.3. 3. Ground Plane.....	8
◇ 1.3. 4. Feeding Mechanism.....	8
1.4. Feeding Techniques of Printed Antennas.....	9
1.4.1. Microstrip Line Feeding.....	9
1.4.2. Coaxial Probe Feeding.....	10
1.4.3. Aperture-Coupled Feeding.....	10
1.5. Parameters and Characteristics of a Patch Antenna.....	11
1.5.1. Directivity.....	11
1.5.2. Gain.....	11
1.5.3. Resonant Frequency and Bandwidth of a Patch Antenna.....	12
1.5.4. Reflection Coefficient (S_{11}).....	12
1.6. Advantages and Disadvantages of a Printed Antenna.....	13
1.6.1. Advantages.....	13
1.6.2. Disadvantages.....	13
1.7. 5G Technology.....	14
1.8. The Use of the 5G Millimeter-Wave Band.....	14
1.9. Printed Antennas in the 5G Millimeter-Wave Band.....	15
1.10. Applications of Printed Antennas in 5G.....	15
Conclusion.....	16

CHAPTER 2

2.1. Introduction	18
2.2. Historical background	18
2.3. Electromagnetic Bandgap (EBG) Structures	19
2.4. Description of EBG Materials	20
2.4.1. Description of Dielectric EBG Materials	20
2.4.1.1. One-Dimensional Lattices	21
2.4.1.2. Two-Dimensional Lattices	21
2.4.1.3. Three-Dimensional Lattices	22
2.4.2. Description of Metallic EBG Structures	22
2.5. Frequency Selective Surfaces (FSS)	23
2.6. Different Types of FSS Element Geometries	24
2.7. Different Types of FSS	25
2.7.1 Patch-Type FSS (Metallic Patches on Dielectric Substrate)	25
2.7.1.1. Influence of Key Parameters on Patch-Type FSS Performance a)	
Lattice Period (Unit Cell Size)	26
2.7.1.2 Different Variants of Patch-Type FSS	26
2.7.2 Grid-Type FSS (Wire Grid FSS)	27
2.8. Field of application of BI	27
2.8.1 In the Optical Domain: Photonic Crystal Fibers	27
2.8.2 Micro-resonators	28
2.8.3 In the microwave domain	29
2.9. Field of application of FSS	29
2.10 Conclusion	30

CHAPTER 3

3.1 Introduction	32
3.2 General presentation of CST MWS	32
3.3. Rectangular Patch Antenna	33
3.3.1. Description of the patch antenna with a conventional substrate	33
3.3.2. Presentation of the single-element structure	35
In this section, a presentation of the single-element structure results will be provided, showing the antenna's characteristics both with slots and without slots.	
3.3.3 Comparison of patch antenna with and without slots	36
3.3.4 Presentation of the patch antenna with slots and patch antenna array structure	38
In this section, a presentation of the single-element structure results will be provided, showing the antenna's characteristics both patch antenna with slots and patch antenna array	
3.3.5 Comparison of patch antenna and patch antenna array	39
3.3.6.presentation of Patch antenna array structure with and without EBG	42
3.3.7. Comparison of patch antenna array with and without EBG	42

3.3.9. Effect of Substrate Material Variation.....	48
3.4. Effect of the FSS Layer.....	51
3.4.1. Frequency Selective Surface (FSS).....	51
3.4.2. How to simulate an FSS layer ?.....	51
3.4.3. Comparison of patch antenna array with EBG and FSS and without FSS	52
3.3.4 Effect of varying the diameter of the motifs of superstrat FSS.....	54
3.4.5. Effect of varying the distance between the patch and the superstrat FSS	56
function of the distance between the patch and the FSS.....	58
General Conclusion.....	59

List of Figures

CHAPTER 1

Figure 1.1 Structure of a printed antenna.....	8
Figure 1.2 Microstrip line feeding.....	10
Figure 1.3 . Coaxial probe feeding.....	10
Figure 1.4. Aperture-coupled feeding.....	11
Figure 1.5. Illustration of the -10 dB bandwidth of an antenna [14].....	12
Figure 1.6. Reflection coefficient (S_{11}).....	13

CHAPTER 2

Figure 2. 1 . Principle of the Bragg Mirror.....	20
Figure 2.2. Examples of 1D, 2D and 3D periodic structures.....	21
Figure 2.3. 1D structure and its dispersion diagram.....	22
Figure 2.4. Examples of various two-dimensional (2D) periodic lattices.....	23
Figure 2.5. Examples of three-dimensional (3D) periodic structures.....	23
Figure 2.6. examples of Frequency Selective Surfaces (FSS).....	24
Figure 2.7. Elementary FSS element geometries.....	26
Figure 2.8. Photograph of a holey fiber, with a core diameter (in the center) of 1 μ m.....	29

CHAPTER 3

Figure 3.1. The main window of the CST softwar.....	34
Figure 3.2. substrate structure without slots.....	36
Figure 3.3. Substrate structure with slots.....	37
Figure 3.4. Reflection coefficient (S_{11}) for the patch antenna with and without slot.....	37
Figure 3.5. 3D directivity pattern of the unslotted antenna.....	37
Figure 3.6. 3D gain pattern of the unslotted antenna.....	38
Figure 3.7. 3D gain pattern of the slotted antenna.....	38
Figure 3.8. Patch antenna with slots.....	40
Figure 3.9. Patch antenna array.....	40
Figure 3.10. Reflection coefficient (S_{11}) for the patch antenna array.....	41
Figure 3.11. Reflection coefficient (S_{11}) for the slotted patch antenna.....	41
Figure 3.12. 3D directivity pattern of the patch antenna array.....	41
Figure 3.13. 3D directivity pattern of the patch antenna.....	42
Figure 3.14. 3D gain pattern of the patch antenna array.....	42
Figure 3.15. 3D gain pattern of the patch antenna.....	43
Figure 3.16. Patch antenna array witout EBG.....	44
Figure 3.17. Patch antenna array with EBG.....	44
Figure 3.18. Reflection coefficient (S_{11}) for the patch antenna array witout EBG	

.....	45
Figure 3.19. Reflection coefficient (S11) for the patch antenna array with EBG.	45
Figure 3.20. 3D directivity pattern of the patch antenna array without EBG.....	45
Figure 3.21. 3D directivity pattern of the patch antenna array with EBG.....	46
Figure 3.22. 3D gain pattern of the patch antenna array.....	46
Figure 3.23. 3D gain pattern of the patch antenna array.....	47
Figure 3.24. Reflection coefficient S11 for different substrate thicknesses.....	48
Figure 3.25. The 3D directivity for a substrate thickness of $h_1 = 5$ mm.....	48
Figure 3.26. The 3D directivity for a substrate thickness of $h_1 = 5.5$ m.....	48
Figure 3.27. The 3D directivity for a substrate thickness of $h_1 = 6$ mm.....	49
Figure 3.28. 3D gain for a substrate thickness of $h_1 = 5$ mm.....	49
Figure 3.29. 3D gain for a substrate thickness of $h_1 = 5.5$ mm.....	49
Figure 3.30. 3D gain for a substrate thickness of $h_1 = 6$ mm.....	50
Figure 3.31. S11 reflection coefficient for the variation of the substrate material	51
Figure 3.32. 3D directivity for (a) $=3.83$ (b) $=3.00$	51
Figure 3.33. 3D directivity for (a) $=3.83$ (b) $=3.00$	52
Figure 3.34. 3D Gain for (a) $=3.83$ (b) $=3.00$	53
Figure 3.35. 3D Gain for (c) $=2.20$ (d) $=3.5$	53
Figure 3.36. Patch antenna array with FSS.....	55
Figure 3.37. patch Antenna array with EBG and FSS and without FSS.....	56
Figure 3.38. 3D directivity for patch antenna array with EBG and FSS, $F =$ (a) and with just EBG (b).....	56
Figure 3.39. 3D gain for patch antenna array with EBG and FSS= (a) and with just EBG (b).....	57
Figure 3.40. Reflection coefficients for different values of the diameter.....	58
Figure 3.41. 3D directivities for the diameter (a) $D = 4.5$ mm (b) $D = 5$ mm.....	59
Figure 3.42. 3D directivities for the diameter (a) $D = 4.5$ mm (b) $D = 5$ mm.....	59
Figure 3.43. 3D directivities for the diameter (C) $D = 5.5$ mm.....	59
Figure 3.44. 3D gain for the diameter (a) $D = 4.5$ mm (b) $D = 5$ mm.....	60
Figure 3.45. 3D gain for the diameter (c) $D = 5.5$ mm.....	60
Figure 3.46. Reflection coefficients for different values of the distance.....	61
Figure 3.47. 3D directivities for the distance (a) $F = 5$ mm (b) $F = 8$ mm.....	61
Figure 3.48. 3D directivities for the distance (C) $F = 10$ mm (D) $F = 13$ mm.....	62
Figure 3.49. 3D directivities for the distance (e) $F = 20$ mm.....	63
Figure 3.50. 3D Gain for the distance (a) $F = 5$ mm (b) $F = 8$ mm.....	63
Figure 3.51. 3D gain for the distance (C) $F = 10$ mm (D) $F = 13$ mm.....	63
Figure 3.52. 3D gain for the distance (E) $F = 20$ mm.....	64

List of Tables

Table 3.1 Dimensions of the rectangular patch antenna.....	34
Table 3 .2 Characteristics of the patch antenna with and without slots.....	37
Table 3 .3. Characteristics of the patch antenna and patch antenna array.....	41
Table 3 .4. Characteristics of the patch antenna array with and without EBG...	45
Table 3.5. Characteristics of the slotted patch antenna as a function of substrate thickness.....	48
Table 3.6. Characteristics of the EBG patch antenna as a function of substrate permittivity.....	50
Table 3.7. Characteristics of a patch antenna array with EBG and with EBG and FSS	53
Table 3.7. Characteristics of a patch antenna array with EBG and FSS for different values of the diameter.....	56
Table 3.8 . Characteristics of The FSS-printed antenna as a.....	58

Abstract

This work focuses on the design and performance enhancement of a microstrip patch antenna for 5G applications using Electromagnetic Band Gap (EBG) structures. The study presents the fundamental concepts of patch antennas, EBG, and Frequency Selective Surface (FSS) structures and investigates their role in improving antenna

performance. Electromagnetic simulations were performed using CST Microwave Studio to evaluate key parameters such as reflection coefficient (S_{11}), resonant frequency, bandwidth, gain, and directivity. The results demonstrate that the integration of EBG structures significantly enhances the overall performance of the antenna, making it a promising solution for future 5G wireless communication systems.

Keywords: 5G, Microstrip Patch Antenna, EBG, FSS, Metamaterials, CST Microwave Studio.

RESUME

Ce travail porte sur la conception et l'amélioration des performances d'une antenne patch microruban destinée aux applications 5G à l'aide de structures à bande interdite électromagnétique (EBG). L'étude présente les concepts fondamentaux des antennes patch, des structures EBG et des surfaces sélectives en fréquence (FSS), ainsi que leur contribution à l'amélioration des performances de l'antenne. Des simulations électromagnétiques ont été réalisées sous CST Microwave Studio afin d'évaluer les principaux paramètres tels que le coefficient de réflexion (S_{11}), la fréquence de résonance, la bande passante, le gain et la directivité. Les résultats obtenus montrent que l'intégration des structures EBG améliore significativement les performances globales de l'antenne, ce qui en fait une solution prometteuse pour les futurs systèmes de communication sans fil 5G.

Mots-clés : 5G, antenne patch microruban, EBG, FSS, métamatériaux, CST Microwave Studio.

ملّخص

يتناول هذا العمل تصميم وتحسين أداء هوائي مطبوع (Microstrip Patch Antenna) مخصص لتطبيقات الجيل الخامس (5G) باستخدام هياكل فجوة الحزمة الكهرومغناطيسية (EBG). تم عرض المفاهيم الأساسية للهوائيات المطبوعة وهياكل EBG والأسطح الانتقائية للترددات (FSS)، مع دراسة دورها في تحسين خصائص الهوائي. أُجريت محاكاة كهرومغناطيسية باستخدام برنامج CST Microwave Studio لتقييم أهم المعايير، مثل معامل الانعكاس (S_{11})، وتردد الرنين، وعرض الحزمة، والكسب، والتوجيهية. أظهرت النتائج أن دمج هياكل EBG يساهم بشكل ملحوظ في تحسين الأداء العام للهوائي، مما يجعله حلاً واعدًا لتطبيقات وأنظمة الاتصالات الألسلكية من الجيل الخامس.

General Introduction

General Introduction

The rapid development of wireless communication systems creates an increasing demand for high-performance antennas capable of meeting the requirements of fifth-generation (5G) networks. These networks provide higher data rates, lower latency, greater connectivity, and improved spectral efficiency compared to previous generations. To achieve these objectives, efficient antenna technologies operating at microwave and millimeter-wave frequencies play a crucial role.

Among the various antenna types, microstrip patch antennas represent one of the most attractive solutions due to their low profile, lightweight structure, ease of fabrication, and compatibility with integrated circuits. Furthermore, their ability to operate at high frequencies and to be integrated into compact wireless devices makes them suitable for modern 5G communication systems.

Despite their advantages, conventional patch antennas suffer from several limitations, including narrow bandwidth, limited gain, and undesirable surface-wave effects. To address these challenges, researchers integrate metamaterial-based structures such as Electromagnetic Band Gap (EBG) and Frequency Selective Surface (FSS) structures. These periodic electromagnetic structures exhibit unique electromagnetic properties that provide better control over wave propagation, leading to improvements in bandwidth, gain, radiation efficiency, and impedance matching.

This work focuses on the design and performance enhancement of a microstrip patch antenna for 5G applications through the incorporation of EBG structures. The study reviews the fundamental principles of patch antennas and their role in modern wireless communication systems. It also presents the concepts of metamaterials, EBG, and FSS structures, highlighting their characteristics and applications in antenna engineering. In addition, electromagnetic simulations using CST Microwave Studio evaluate and compare the performance of conventional and EBG-loaded patch

antennas through key parameters such as the reflection coefficient (S_{11}), resonant frequency, bandwidth, gain, and directivity.

The main objective of this work is to demonstrate the effectiveness of EBG structures in enhancing the overall performance of microstrip patch antennas for next-generation 5G wireless communication systems.

CHAPTER 1
Printed Antenna in the 5G
Band

1.1. Introduction

With the rapid evolution of 5G wireless technology, the demand for compact and high-performance antennas has significantly increased [1]. Among the most suitable candidates, patch antennas (microstrip antennas) have gained considerable attention due to their low profile, ease of fabrication, and compatibility with integrated circuits [2].

In 5G systems, especially at microwave and millimeter-wave frequencies (such as sub-6 GHz and above 24 GHz), antennas must support high data rates and efficient signal transmission. [1] Patch antennas are well-suited for these requirements, as they can be designed in various geometries and easily integrated into antenna arrays [3].

Moreover, their ability to operate at high frequencies and to be arranged in arrays makes them essential for advanced 5G technologies such as beamforming and MIMO, which are key to improving capacity, coverage, and overall system performance [4-5].

1.2. Definition of Patch Antenna

A patch antenna, also known as a microstrip antenna, is a flat and compact type of antenna. It consists of a metallic patch (often rectangular or circular) placed on a dielectric substrate, with a ground plane on the opposite side. It operates by transmitting and receiving electromagnetic waves, typically in the microwave frequency range [1-2].

Radiation occurs due to the fringing fields at the edges of the patch, which extend beyond the metal surface and radiate energy into the surrounding space [1].

Patch antennas are widely used because they are simple, lightweight, low-cost, and easy to integrate into printed circuit boards. Their performance can be controlled by adjusting the shape and size of the patch, the properties of the substrate, and the feeding method [2-3].

These characteristics make them suitable for many wireless communication applications, including satellites, radar systems, GPS, and IoT [3]. They are especially important in 5G networks, where they are used in arrays to support advanced techniques such as beamforming and MIMO, enabling efficient and flexible communication systems [4-5].

1.3. Structure of a Printed Antenna

◇ 1.3. 1. Radiating Patch

The radiating patch is a metallic layer, usually made of copper or gold, placed on top of a dielectric substrate. It is responsible for radiating energy into the surrounding space [1].

The patch can take different shapes such as rectangular, circular, or triangular. Its dimensions play a key role in determining the antenna's operating frequency and overall performance [1-2].

◇ 1.3. 2. Dielectric Substrate

The dielectric substrate is a material that insulates the patch from the ground plane. It helps the antenna work better by affecting how energy it can send out and how well it matches the signal [1-3]. Common materials used for the substrate are FR4 and Rogers. These materials help the antenna work efficiently [2-3].

◇ 1.3.3. Ground Plane

The ground plane is a metal layer, on the bottom of the substrate [2]. It helps direct the waves outward [1]. This improves the antennas performance by making the radiation pattern more stable and reducing losses [3].

◇ 1.3.4. Feeding Mechanism

The feeding mechanism is how the antenna gets its power [1]. It connects the antenna to the transmission line or source. There are ways to feed the antenna including :

- * Microstrip line feed [4]
- * Coaxial probe feed [4]
- * Aperture coupling [5]
- * Proximity coupling [5]

Each feeding method affects how well the antenna matches the signal and how bandwidth it uses [2]. The microstrip patch antenna uses these components to work [1]. The radiating patch sends out the signal. The substrate and ground plane help the patch work efficiently. The feeding mechanism makes sure the antenna gets the power it need.

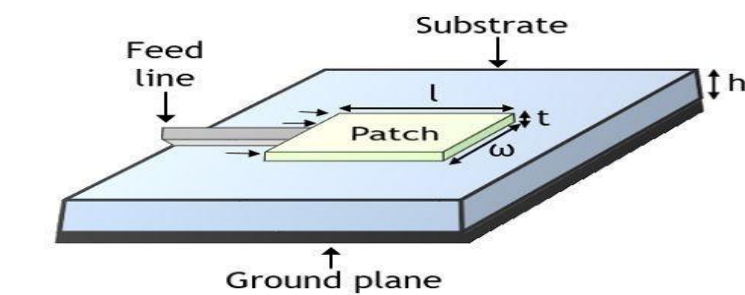


Figure 1.1. Structure of a printed antenna [6].

1.4. Feeding Techniques of Printed Antennas

Printed antenna feeding techniques help transfer power from the transmission line to the radiating patch [2]. This is done while making sure the impedance matches properly [4].

There are common techniques used :

1.4.1. Microstrip Line Feeding

Microstrip line feeding is a technique that uses a conducting microstrip line printed on the same substrate as the patch antenna [2]. It is widely used because it is simple to design and fabricate [2].

This feeding method helps achieve impedance matching between the transmission line and the antenna [1]. However, it may introduce unwanted radiation losses and typically provides a limited bandwidth compared to other feeding techniques [2].

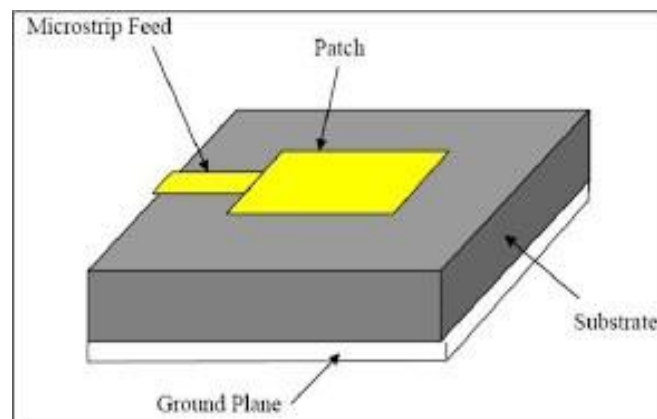


Figure 1.2. Microstrip line feeding.

1.4.2. Coaxial Probe Feeding

In this technique, a coaxial cable's inner conductor is connected directly to the radiating patch while the outer conductor is attached to the ground plane [2]. It provides

good impedance matching, supports wide bandwidth, and minimizes spurious radiation, making it suitable for high-performance patch antenna [4].

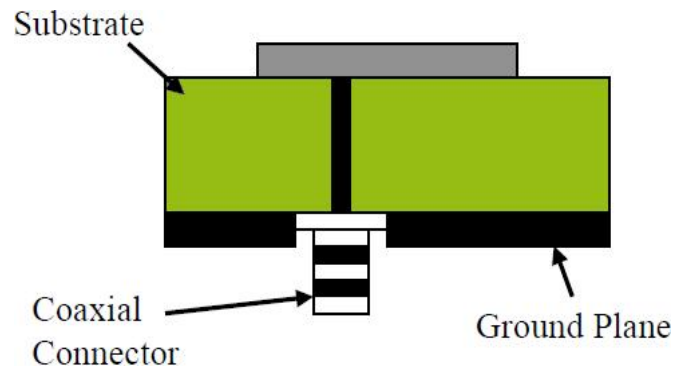


Figure 1.3. Coaxial probe feeding.

1.4.3. Aperture-Coupled Feeding

This feeding method transfers energy from the feed line to the patch antenna through a slot or aperture in the ground plane [5]. It offers good isolation between the feed and the patch, improves impedance matching, and can enhance bandwidth and radiation characteristics.[4]

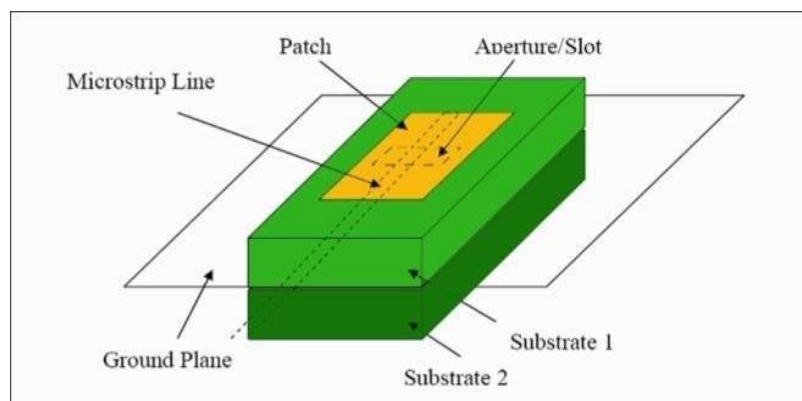


Figure 1.4. Aperture-coupled feeding.

1.5. Parameters and Characteristics of a Patch Antenna

1.5.1. Directivity

The directivity of a patch antenna is a measure of how the power it sends out is focused in one direction. This is compared to an antenna that sends out power equally in all directions [1]. The directivity of a patch antenna shows how well it can send energy in the direction it is pointing. This is important for things like 5G and wireless systems because it helps make the signal stronger and travel farther [3].

1.5.2. Gain

The gain of a patch antenna is a measure of how effectively it converts input power into radiated energy in a specific direction. It combines both the antenna's directivity and efficiency, reflecting not only how focused the radiation is but also how much power is actually radiated rather than lost as heat [2].

1.5.3. Resonant Frequency and Bandwidth of a Patch Antenna

The resonant frequency is the frequency at which the patch antenna radiates most efficiently, determined by the patch dimensions and substrate properties. The bandwidth is the range of frequencies where the antenna operates effectively, usually limited in patch antennas but can be improved with design techniques like thicker substrates or stacked patches.

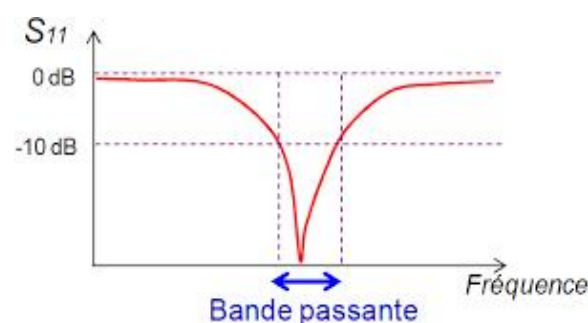


Figure 1.5. Illustration of the -10 dB bandwidth of an antenna [14].

1.5.4. Reflection Coefficient (S_{11})

The reflection coefficient (S_{11}) tells us how much power is sent back from the antenna input because of a mismatch in impedance. It is measured in decibels (dB). A low value, usually -10 dB or lower means the antenna is well matched. This also means that most of the input power is radiated, not reflected. S_{11} is very important to know how well a patch antenna work. It helps us find out the antennas efficiency and bandwidth. We often use S_{11} when making measurements, with a network analyzer.

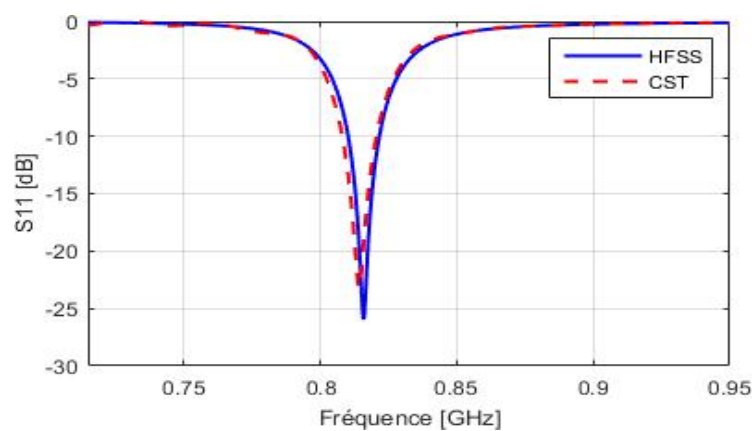


Figure 1.6. Reflection coefficient (S_{11}).

1.6. Advantages and Disadvantages of a Printed Antenna

1.6.1. Advantages

- **Compact and Lightweight :** Easy to integrate into modern devices [1]
- **Low Cost:** Simple fabrication using printed circuit board (PCB) technology [1]
- **Planar Structure:** Suitable for arrays and conformal applications [5]
- **Ease of Integration:** Can be easily combined with circuits and electronics [2]
- **Versatile Design:** Patch shape and size can be adjusted for desired frequency, polarization, and radiation characteristics [2].

1.6.2. Disadvantages

- **Narrow Bandwidth** : Limited frequency range compared to other antennas [3] ;
- **Moderate Gain** : Usually lower than high-gain antennas unless used in arrays [3] ;
- **Low Power Handling** : Not suitable for high-power applications [2] ;
- **Surface Wave Losses** : Can reduce efficiency, especially with high-dielectric substrates.

1.7. 5G Technology

The IMT-2020 technologies of the fifth generation (5G) are underway, and they have immense transformative potential to make our lives better [6]. Better healthcare, smarter cities, and a much more efficient industry—all of this becomes possible as the internet grows and comes with a wide range of innovative solutions that drive our modern economy [7]. However, without 5G networks, none of these can reach their full potential.[8] Soon, intelligent systems will become essential to meet the strong demand for data from billions of people using ever-increasing amounts of video every day [9]. 5G will enable much faster data rates, reliable connectivity, and low latency for international mobile telecommunications (IMT)—all key to our new global communications ecosystem, made up of connected devices sending large amounts of data via ultra-high-speed broadband [6].

The 700 MHz band has been exclusively assigned to 5G [10]. Operators can also use the 800 MHz and 2.6 GHz bands, already assigned to 4G, but only if spectrum is available [11]. In the long term, the 3.5 GHz band will also be assigned to 5G [12].

1.8. The Use of the 5G Millimeter-Wave Band

The 5G millimeter-wave band enables very high data rates, low latency, and supports a large number of connected devices [6]. It is mainly used in dense environments such as cities, stadiums, and other crowded areas where high network capacity is required [13].

However, because millimeter-wave signals have short wavelengths and higher propagation losses, they are easily affected by obstacles and attenuation [14]. Therefore, advanced antenna technologies such as beamforming, massive MIMO, and patch antenna arrays are required to maintain reliable coverage and efficient communication [15].

These techniques help focus the signal directionally and improve overall system performance, making millimeter-wave 5G suitable for high-demand communication scenarios [16].

1.9. Printed Antennas in the 5G Millimeter-Wave Band

Printed antennas play an important role in the 5G millimeter-wave band due to their compact structure and ease of integration into modern communication systems [1]. Their planar design allows them to be fabricated directly on printed circuit boards, making them suitable for high-density electronic devices [2].

In millimeter-wave frequencies, these antennas can be integrated into large-scale arrays, which are essential for implementing advanced signal processing techniques such as beam steering and spatial multiplexing [14]. This enables more efficient use of the spectrum and improved system performance [15].

Their compatibility with integrated circuit technology also makes them a practical solution for compact 5G modules, including user equipment, base stations, and small-

cell infrastructure [17]. As a result, printed antennas are a key enabling technology for supporting high-capacity wireless communication in dense deployment scenarios [18].

1.10. Applications of Printed Antennas in 5G

Printed antennas are a fundamental technology in modern 5G systems, enabling compact, efficient, and high-performance solutions for advanced wireless communication applications [19], among which we mention :

- * 5G Smartphones and User Devices : they help these devices send and receive data quickly and connect to many different frequency bands [19].
- * Base Stations and Small Cells : Printed Antennas are used together to form an array, which helps with beamforming and massive MIMO making the signal stronger and covering more area [20].
- * Internet of Things Devices : Printed Antennas are used in these devices because they are small and work well which is important for sensors and smart devices that need to be connected to the internet [21].
- * Vehicular Communications : Printed Antennas help cars and other vehicles communicate with each other at frequencies, which is necessary for autonomous vehicles and smart traffic systems [22].

1.11. Conclusion

In summary, patch antennas represent a practical and widely adopted solution for meeting the requirements of modern 5G wireless systems [1]. Their planar structure and compatibility with printed circuit technology allow seamless integration into compact and multifunctional communication modules [2].

Their use in advanced network architectures supports the development of more efficient and flexible wireless systems, contributing to improved overall network performance . This makes them an important component in the evolution of next-generation communication technologies.

CHAPTER 2
EBG and FSS Materials

2.1. Introduction

Periodic electromagnetic structures known as metamaterials have attracted considerable attention in telecommunications due to their engineered properties, enabling advanced radiofrequency devices and antenna enhancements [23]

Metamaterials are artificially structured composites achieving tailored permittivity (ϵ) and permeability (μ), potentially negative, leading to Double-Negative (DNG) or Left-Handed Materials (LHM) [24-25].

Key structures for antenna engineering include Frequency Selective Surfaces (FSS), two-dimensional periodic arrays of metallic patches or apertures acting as spatial filters for selective reflection or transmission based on frequency, polarization, and angle[26-27], and Electromagnetic Band Gap (EBG) structures, periodic arrangements inhibiting wave propagation in specific bands[28-29].

The objective of this chapter is to present fundamental concepts of EBG and FSS structures and analyze their role in enhancing microstrip patch antennas for 5G millimeter-wave applications.

2.2. Historical background

The concept of periodic electromagnetic structures, which later became known as Electromagnetic Band Gap (EBG) or BIE materials, traces its origins to the early 20th century. In 1915, the English physicist William Laurence Bragg demonstrated that a periodic stack of transparent layers with differing refractive indices could reflect up to 99.5% of incident light. This effect, unattainable with conventional mirrors, results from multiple reflections within each interface, producing constructive interference at specific layer thicknesses. These early one-dimensional structures are now referred to as Bragg mirrors [30].

At the end of the 1980s, E. Yablonovitch extended this concept to two- and three-dimensional periodic structures [31-32], aiming to control electromagnetic wave

propagation across multiple directions. These structures, initially prototyped at microwave

frequencies for practical measurement, exhibit frequency bands—known as band gaps—within which no electromagnetic mode can propagate [33]. This principle forms the foundation of modern EBG/BIE materials..

Over the decades, research on EBG structures has expanded significantly, covering a broad frequency spectrum. Optical frequencies, ranging from approximately 1 THz to 1000 THz, as well as microwave and millimeter-wave frequencies, are explored to design devices with tailored electromagnetic responses. These developments have enabled the realization of high-performance radiofrequency components, including antennas, filters, and waveguides, and are particularly relevant for emerging technologies such as 5G millimeter-wave patch antennas [34]. **Figure 2.1.**

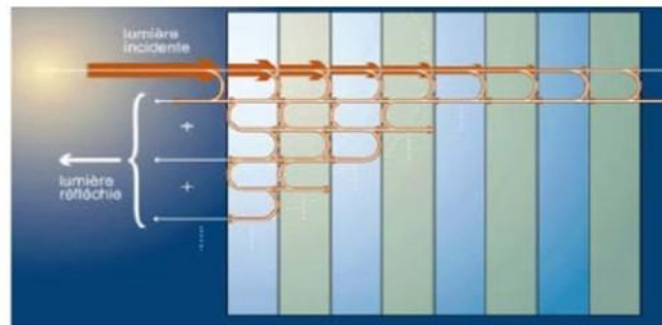


Figure 2.1. – Principle of the Bragg Mirror

2.3 Electromagnetic Bandgap (EBG) Structures

These surfaces are periodic structures of dielectric and/or metallic materials, generally referred to as Electromagnetic Band Gap (EBG) structures, which are extrapolated from photonic band gap structures [28-29]. These artificial structures have the property of suppressing surface wave propagation [35]. These structures are used as

frequency filters, spatial filters, or mirrors with very high reflectivity[26]. Among the most commonly used cells, the Double Split Ring Resonator (DSRR) is cited[36]

2.4 Description of EBG Materials

2.4.1 Description of Dielectric EBG Materials

For semiconductor materials, the objective was to control the electrical properties of the materials. With EBG materials, we aim to achieve control over their electromagnetic properties [23] .

EBG materials are periodic structures with one, two, or three directions of periodicity, composed of dielectric or metallic elements [29](Figure 2.2). They have the property of controlling the propagation of electromagnetic waves [28.] These structures can act as frequency filters and spatial filters [26].

Since the incidence of waves is a limiting factor on the performance of these structures, researchers working in fields using these materials have attempted to develop isotropic EBG structures that maintain their properties regardless of the angle of incidence of the waves [35].

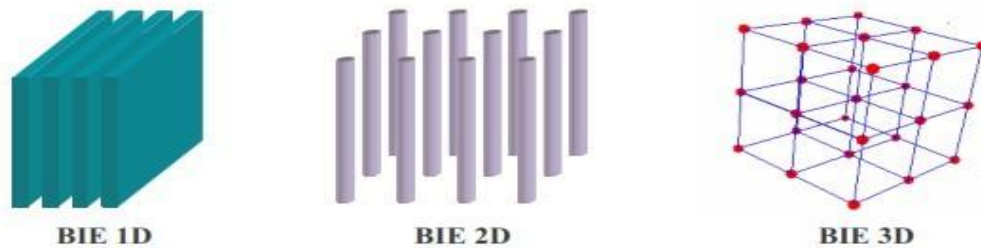


Figure 2.2Examples of 1D, 2D and 3D periodic structures

2.4.1.1 One-Dimensional Lattices

One-dimensional (1D) structures are the oldest, although they have only recently been integrated into EBG structures. Indeed, they have been extensively studied and used as dielectric mirrors or optical filters [28].

They consist of stacking several layers of materials with different permittivities (principle of the Bragg mirror[94]. The band gaps are larger as the index contrast is higher for structure thicknesses equal to a quarter of the guided wavelength [28].

.(Figure 2.3).

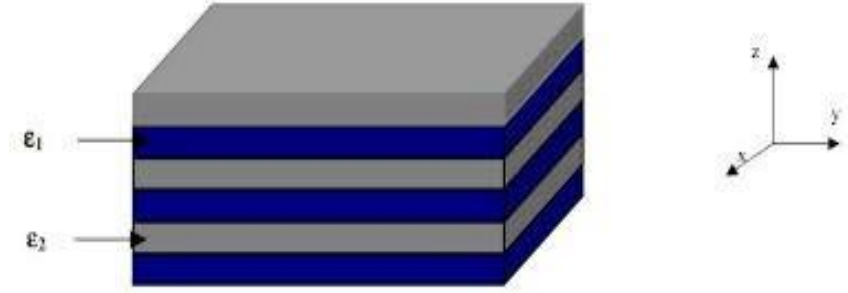


Figure2 .3.1D structure and its dispersion diagram

2.4.1.2 . Two-Dimensional Lattices

Two-dimensional (2D) materials are crystals whose dielectric constant is structured periodically in two dimensions and remains homogeneous in the third [28]. We can therefore study electromagnetic waves incident on the 2D structure in two distinct polarizations: TE (electric field parallel to the bars of the structure) and TM [33] (electric field perpendicular to the bars).

The frequency behavior is not necessarily identical depending on the polarization. Indeed, the appearance of band gaps depends on the index contrast[32], which must be higher depending on the type of network. We present in Figure 2.4 several types of networks such as the square network, the triangular network, or the hexagonal network [28].

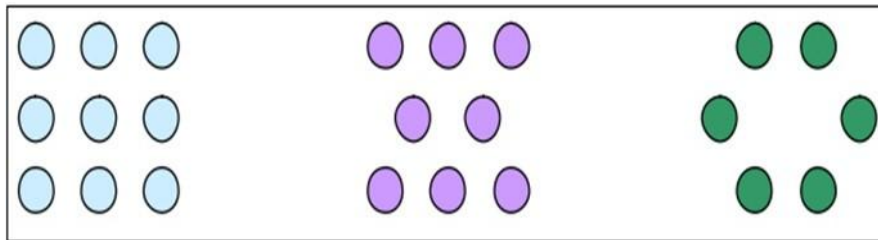


Figure 2.4. Examples of various two-dimensional (2D) periodic lattices.

2.4.1.3 Three-Dimensional Lattices

Three-dimensional (3D) structures are the first structures studied alongside 1D structures or Bragg networks. The objective was to obtain 3D structures operating on the same principles as Bragg mirrors but possessing a complete photonic band gap [31], that is, in all directions of space [33]. There exists a large number of possible structures (Figure 2.5.)

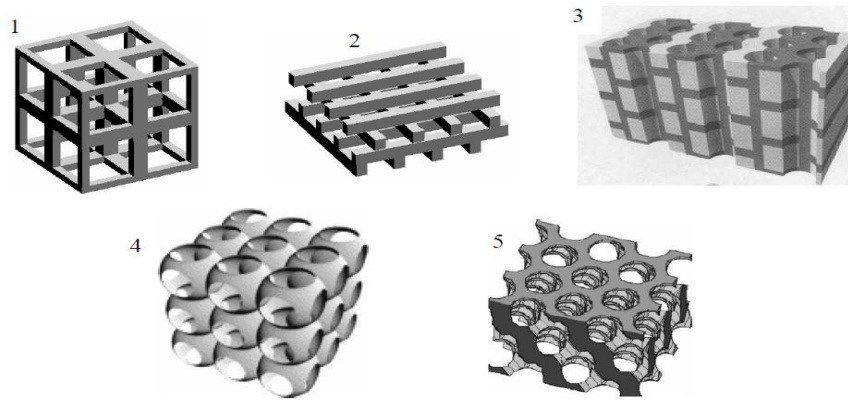


Figure 2.5 . Examples of three-dimensional (3D) periodic structures.

2.4.2 . Description of Metallic EBG Structures

The first band gap materials were realized with purely dielectric materials to meet applications in the field of optics. Indeed, in this domain, the use of metallic structures was difficult because there were strong losses in metals at these frequencies[28]. On the other hand, at microwave and radiofrequency frequencies, losses become negligible in some cases. Metals are therefore quasi-perfect reflectors with low absorptions. For frequencies on the order of gigahertz, the skin depth d is very small compared to the wavelength, which is well below optical frequencies [37].

About fifty years ago, the first studies focused on metallic elements possessing different axes of periodicity in order to realize polarizers and reflectors. They also allowed the design of Frequency Selective Surfaces or FSS [26] (Figure 2.8), but most concern single-layer structures with 1D or 2D patterns. Metallic EBG structures, or commonly called

EBGM, are an extension of these periodic metallic networks to multi-layer networks with several dimensions [29]



Figure 2.6 .— Examples of Frequency Selective Surfaces (FSS).

2.5 . Frequency Selective Surfaces (FSS)

Frequency Selective Surfaces (FSS) have been the subject of various studies , such as frequency filtering to attenuate unwanted signals and limit interference phenomena, and controlling antenna characteristics such as gain, directivity, and bandwidth [26]

FSS are generally composed of metallic and dielectric elements [27] arranged in planar periodic arrays The reaction of an FSS to excitation is determined by the geometry of the periodic patterns, the grid spacing, and their dispersion properties, generally established when considering infinite surfaces, and resonance phenomena appear when the effective size of the network elements is a multiple of the excitation wavelength . Indeed, after the electromagnetic wave passes through the FSS, certain frequencies are transmitted while others are reflected [35].

FSS surfaces have been used for military applications since the 1960s to make objects undetectable by radars [38], such as stealth aircraft, or inserted into radomes to protect the antenna from weather [39]

2.6 . Different Types of FSS Element Geometries

Despite the numerous years of research on FSS, new models continue to appear and will undoubtedly continue to emerge. As shown by Munk , the motifs used in FSS are classified into four basic groups see Figure (2.10) [26]

Group 1: Formed by elements connected at the center with N poles, such as dipoles, tripods, and Jerusalem crosses. The most popular elements in this group are: (a) Jerusalem cross (b) tripodes [27] . Some of these elements have been combined with other types to produce new FSS configurations.

Group 2: Ring types, such as circular, square, and hexagonal rings [35]. This group is probably the most popular, with numerous articles written on square rings, simple and concentric rings . Tripolar rings also fall into this category. Group 3: Formed by openings of any shape in a conductive plane or patches of various shapes printed on a substrat[29]. These structures generally take the form of openings or patches. They can appear in multi-layer or single-layer configurations. The single-layer configuration with openings is used as dichroic filters [38] .

Group 4: Combinations of the above elements [39]. Combinations of different types of FSS elements have been employed in recent years to mitigate some of the problems associated with FSS composed of a single type of element (motif). For example, an FSS formed by square rings with slots has been used to attempt to overcome the angular sensitivity problems observed in FSS formed by square rings alone. These new structures have also been used to reduce the RCS (Radar Cross Section) of radomes . These four basic models can be combined to generate numerous new FSS with unique characteristics. [28]

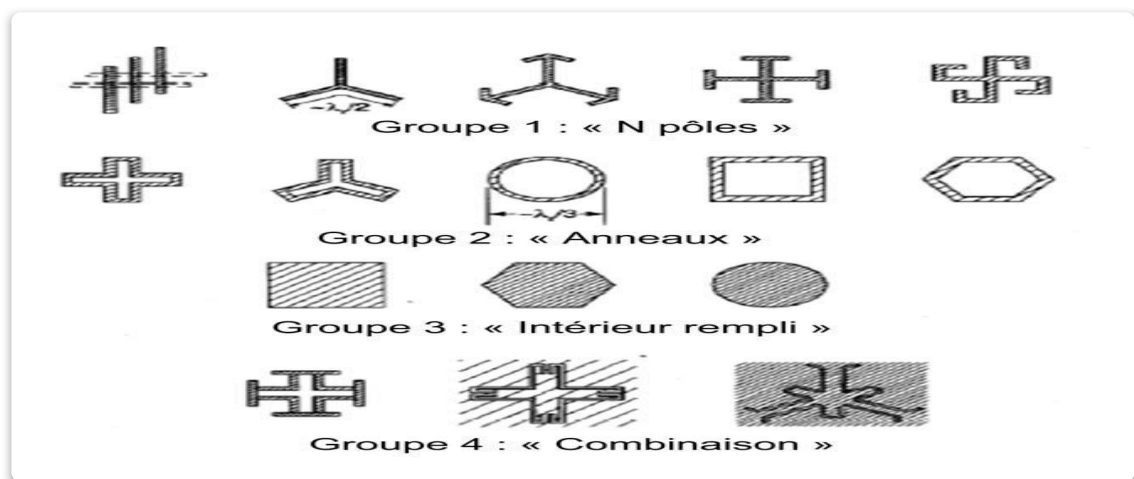


Figure 2..7– Elementary FSS element geometries.

After Munk, 2000))

2.7 Different Types of FSS

2.7.1 Patch-Type FSS (Metallic Patches on Dielectric Substrate)

Frequency Selective Surfaces (FSS) with etched motifs are generally equivalent to a low-pass filter [26].

At low frequencies, the dielectric structure of the screen causes only attenuation of the wave, depending on the permittivity and loss tangent of the medium considered [27]. At high frequencies, the motif then resonates, the induced current on the metallizations is significant, and causes the reflection of the incident wave [35].

The efficiency of the reflection depends on various parameters, such as the geometry of the etchings, their size relative to the period of the network, but also the permittivity or the thickness of the substrate on which the motif is printed [29].

1.7.1.1 Influence of Key Parameters on Patch-Type FSS Performance

a) Lattice Period (Unit Cell Size)

When the network period is varied, the variation is mainly present in the bandwidth of the response. For the same motif size, the smaller the period, the greater the bandwidth will be [26]

b) Influence of Substrate Thickness

Varying the substrate thickness causes a shift in the motif's resonance frequency. However, this shift tends towards a limit when the substrate reaches a thickness of a few millimeters [29]

c) Influence of Substrate Permittivity

A variation in the substrate permittivity has the same consequences as modifying the dimensions of the motif:

The resonance frequency is modified. By increasing the substrate permittivity, the resonance frequency of the patches decreases. This observation is very problematic, as

most manufacturers cannot certify the permittivity value of their materials to less than $\pm 2\%$ for high indices [40]

2.7.1.2 Different Variants of Patch-Type FSS

There exists a multitude of variants both at the level of motifs and at the level of material stacks.

There are single-layer FSS formed by patches printed on substrate; multi-layer FSS, where the patches are sandwiched between substrates, and many other configurations [26].

2.7.2 Grid-Type FSS (Wire Grid FSS)

Grids or perforated metallic plates have a frequency behavior of the high-pass type [27].

At low frequencies, the dichroic grid is seen as a perfectly conducting plane, the incident wave is therefore totally reflected.

At high frequencies, the predominant effect is that of the holes. The frequency of the incident wave being higher than the cutoff frequency of the guide, we therefore have guided propagation. The signal is then mainly transmitted [35].

FSS grids are widely used in the microwave domain [29]. The shape and size of the openings, their periodicity, the thickness of the metallic screen, determine the frequency behavior of the FSS. The most common openings are rectangular or circular [38] cross-shaped openings are also used. Openings with more complex shapes and multiple-screen grids are sometimes used to achieve specific performances or to meet very tight design specifications [39].

2.8 Field of application of BI

In this part, we will describe the different possible applications of electromagnetic band gap materials. We will limit ourselves to the case of two-dimensional photonic crystals, which are those that currently offer several applications [28]. First, we will discuss the optical domain, then we will address the microwave domain [29].

2.8.1 In the Optical Domain: Photonic Crystal Fibers

Photonic crystal fibers have already entered the field of industrial applications. They were first proposed in the 1990s [41]. These fibers are obtained by stacking several silica tubes to obtain a 'preform'. This preform is then heated to a very high temperature of about 1800°C and then drawn to obtain a diameter of about 125μm, to be similar to a conventional fiber. The fiber is then protected by a plastic sheath [42]

As can be seen in the graph of Figure 2.8.

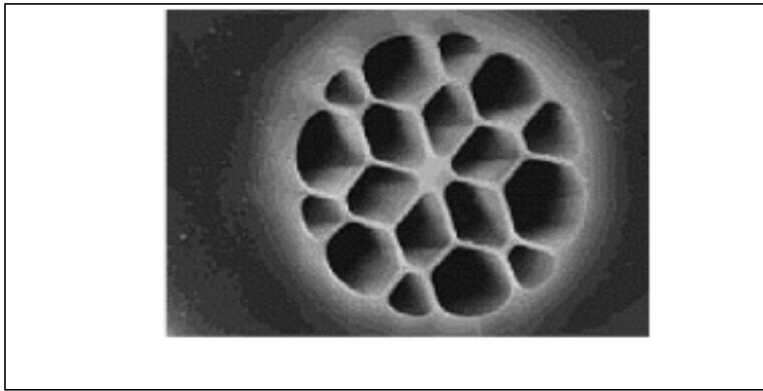


Figure 2.8. Photograph of a holey fiber, with a core diameter (in the center) of 1μm

These electromagnetic crystal fibers also possess dispersion properties that can be controlled through their geometric parameters [43].

2.8.2 Micro-resonators

The use of point and linear defects allows for the creation of micro-resonators and waveguides, respectively. The realization of micro-resonators is obtained by including point defects in an electromagnetic crystal structure. The first studies on micro-resonators with two-dimensional structures were carried out in 1997 by Labilloy [44]. Waveguides: The idea of realizing waveguides appeared in 1994 and the first realizations arrived in 1999 [45] Linear waveguides present many losses.

There is another type of waveguide called 'bent waveguide' or 'waveguide with turn' [46]

Filters and multiplexers: An important function that can be realized with electromagnetic crystals is wavelength multiplexing (WDM, Wavelength Division Multiplexing). The objective is to insert or extract very precise wavelengths. Several

realizations have shown the possibility of coupling a cavity with a guide. For example, the realization allows the extraction or insertion in a guide of a very precise wavelength [47]

2.8.3 In the microwave domain

A large number of research teams have been interested in the study of EBG at microwave frequencies due to the multiple applications conceivable in this frequency domain. The Telecommunications sector, particularly antennas, is very concerned. Indeed, one can use photonic band gap materials for the realization of:

- Antenna substrates: The first experiments aiming to exploit dielectric electromagnetic crystals as antenna substrates were conducted by ER. Brown et al . [48].
- High-impedance surfaces: Can be used to improve the directivity of antennas [49] .

EBG can also be used in the realization of microwave circuits such as

- Planar filters;
- Waveguides;
- Multiplexers;

Improvement of antenna efficiency by using substrates based on ultra-refractive electromagnetic crystals [50]

2.9. Field of application of FSS

Originally, FSS technology was part of the military domain. Today, FSS have found numerous applications in microwave electromagnetism, radar antennas, satellite communications. Among these various applications, one can cite:

- Radomes
- Reflectors

- Filters
- Absorber

2.10 Conclusion

This chapter is briefly dedicated to periodic BIE materials; dielectric and metallic BIE materials (FSS) [51-52]

First, it allowed us to present the essentials of the theory or a brief history on electromagnetic band gap (EBG) structures with and without defects, and the description of dielectric and metallic BIE materials and their applications. Finally, we tried to collect the most important information on FSS by mentioning its most important principles and different forms, and we showed some domains of its applications [53].

CHAPTER 3
Results and Discussion

3.1 Introduction

This chapter is devoted to the presentation of the different simulations and results, which are mainly focused on improving the performance of patch antennas. We will first provide a description of the CST Microwave Studio used for the simulations, highlighting the selected frequency range corresponding to 5G applications. Then, a comparison between a patch antenna without and with a EBG structure will be carried out in terms of key characteristics, such as the reflection coefficient (S_{11}), resonant frequency, bandwidth, gain, and directivity.

3.2 General presentation of CST MWS

CST Microwave Studio is a widely used software for three-dimensional electromagnetic simulation and analysis. It enables accurate modeling of electromagnetic wave behavior using advanced numerical techniques, making it a powerful tool for studying complex electromagnetic structures.

This software provides an integrated environment for designing and analyzing various systems by allowing the definition of geometrical structures, material properties, and excitation conditions. It also offers the ability to obtain important results such as reflection coefficient, resonant frequency, gain, and directivity, which are essential for evaluating system performance.

Several other software tools offer similar functionalities, including ANSYS HFSS, FEKO, and COMSOL Multiphysics. However, CST Microwave Studio was chosen in this work due to its user-friendly interface, high simulation speed, and accuracy, as well as its advanced analysis capabilities, which make it particularly suitable for achieving the objectives of this study.

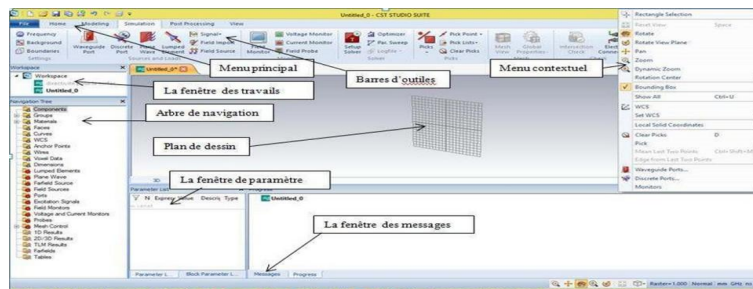


Figure 3.1. The main window of the CST softwar

The navigation tree is an essential element of the user interface. From it, we can access structural elements as well as simulation results. The following sections explain the different items within this tree window.

Context menus provide a flexible way to access the most frequently used menu commands depending on the current context. This menu can be opened by right-clicking the mouse.

The drawing plane is the plane on which we draw the primitives of the structure. Since the mouse is only a 2D locator, even when defining 3D structures, coordinates must be projected onto the drawing plane in order to specify a 3D position. As the position and orientation of the drawing plane can be modified using different tools, this feature makes the modeler very powerful.

The parameter window displays a list of all previously defined parameters along with their current values.

The message window shows informational text (for example, solver output) when available.

The other user interface elements are standard for a Windows-based application.

3.3. Rectangular Patch Antenna

3.3.1. Description of the patch antenna with a conventional substrate

We selected a rectangular patch antenna consisting of multiple layers. The first layer is the ground plane, with a length of 86 mm, a width of 62 mm, and a thickness of $h_g = 0.035$ mm. Above it lies the dielectric substrate layer, which has a thickness

of $h_s = 1.6$ mm and shares the same length and width as the ground plane. Next, we created a patch with a width of $W_p = 44$ mm and a length of $L_p = 44$ mm.

Thus, we obtained a conventional patch antenna, from which certain parts were etched (removed). The simulated antenna operates in the 3.5 GHz band (5G), and its dimensions are summarized in Table 3.1.

Table 3.1: Dimensions of the rectangular patch antenna with a conventional substrate

Parametric Dimensions	Value (in mm)
hs :substrate thickness	1.6
Wg : Substrate width	62
Lg : Substrate length	86
hp = Hg : Ground plane thickness	0.035
S : Patch surface area	3525.88mm ²

After conducting multiple simulation runs and systematically tuning various parameters, acceptable results were achieved by fixing the parameter values. Specifically, the antenna length was set to $L = 40$ mm and the width to $W = 44$ mm, targeting an operating frequency within the 3.5 GHz band with an excellent impedance matching. The dielectric material utilized for the substrate is "EPOXY RESIN " with a relative permittivity of $\epsilon_r = 4.5$.

This configuration yielded satisfactory performance for the patch antenna using the these dimensions. Additionally, specific parts were etched (slots were introduced) to optimize the design.

3.3.2. Presentation of the single-element structure

In this section, a presentation of the single-element structure results will be provided, showing the antenna's characteristics both with slots and without slots.

- **Without slots**

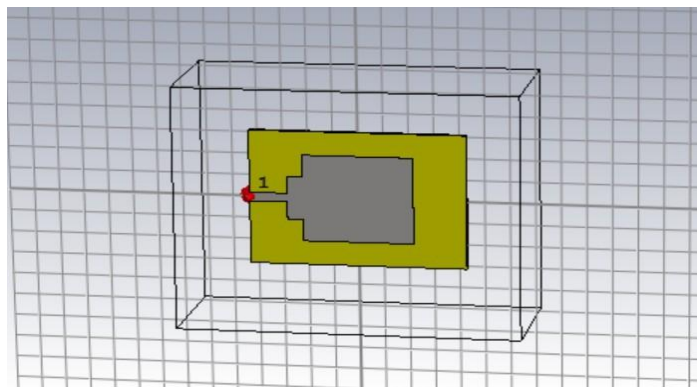


Figure 3.2. Substrate structure without slots

- **With slots**

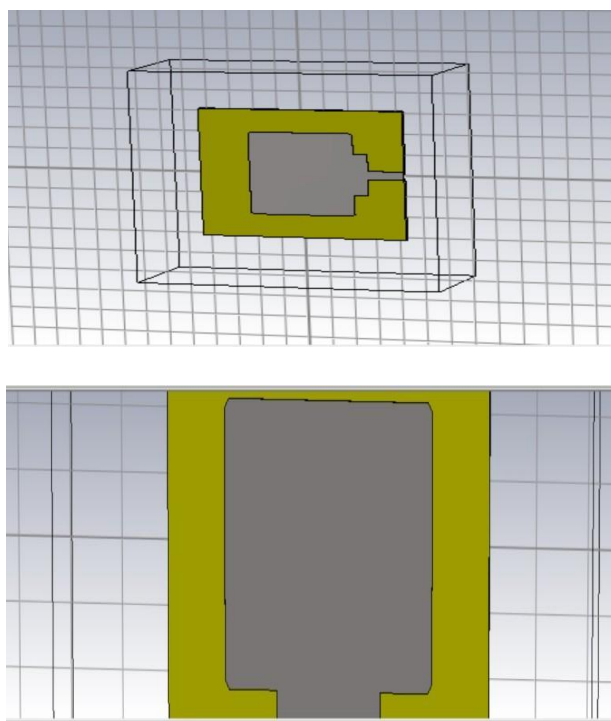


Figure 3.3. Substrate structure with slots

3.3.3 Comparison of patch antenna with and without slots

In this section, a comprehensive performance comparison of the patch antenna will be presented. We will compare and analyze the antenna's characteristics with slots, and without slots to evaluate their impact on the overall performance

A) Resonant frequency

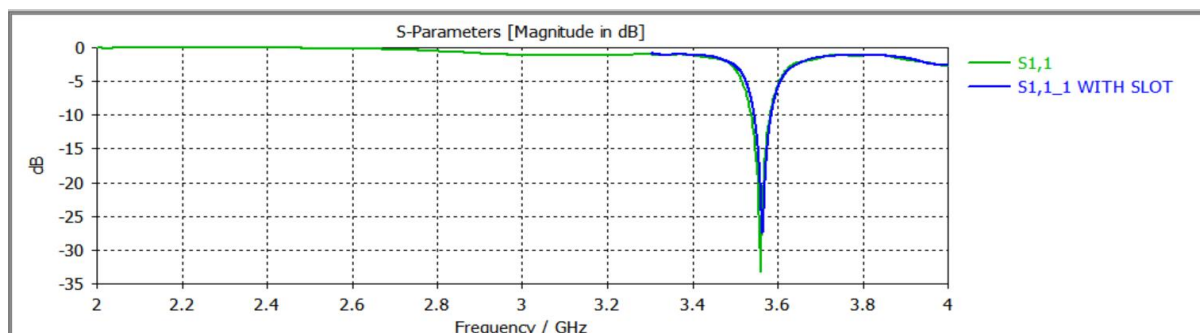


Figure 3.4. Reflection coefficient (S11) for the patch antenna with and without slot

A) Directivity

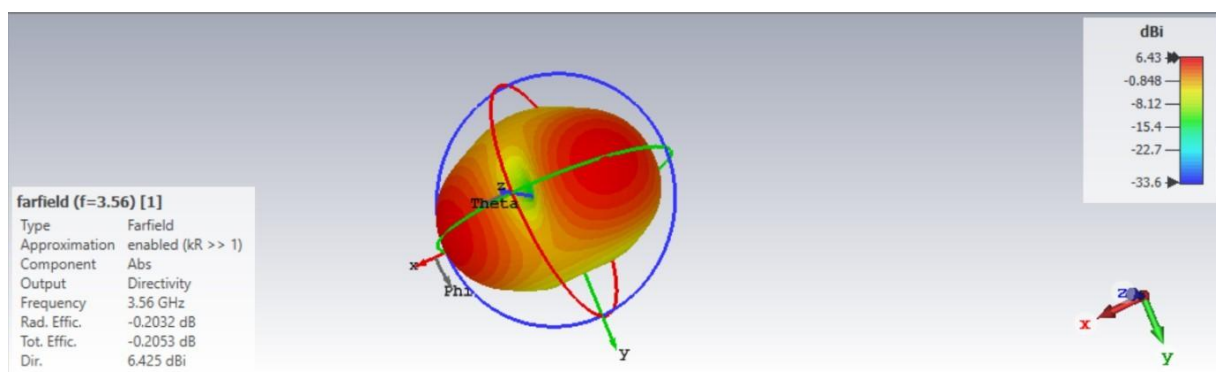


Figure 3.5. 3D directivity pattern of the unslotted antenna

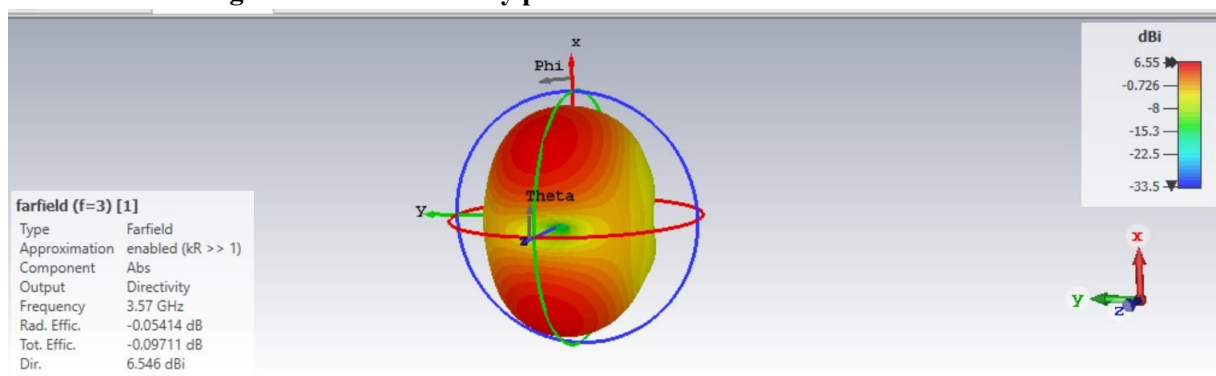


Figure 3.6. 3D directivity pattern of the slotted antenna

B) Gain

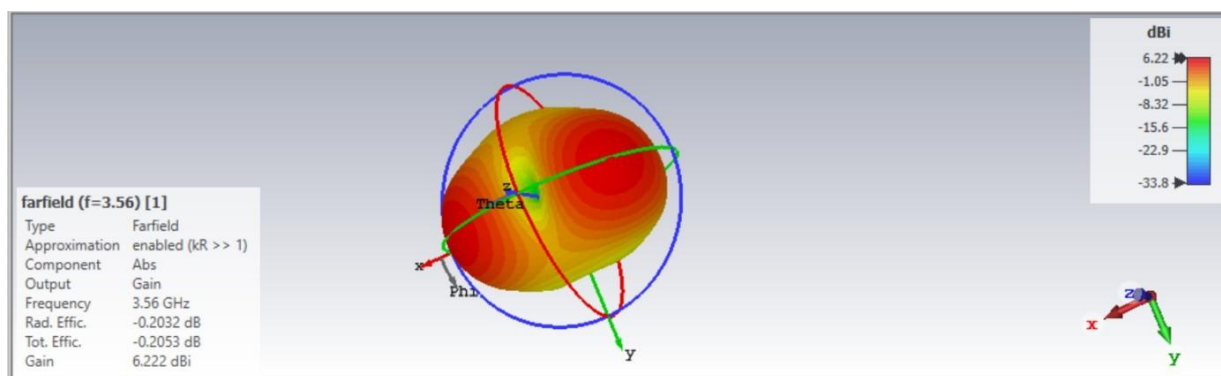


Figure 3.7. 3D gain pattern of the unslotted antenna

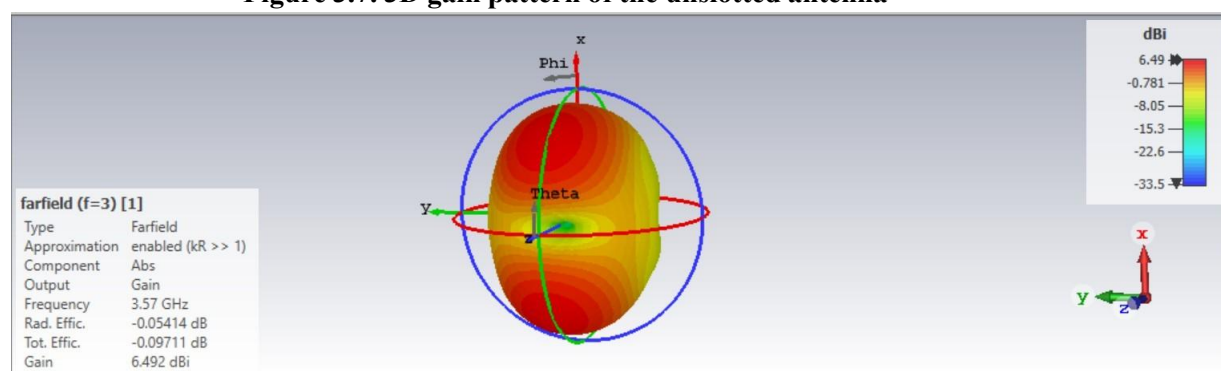


Figure 3.8. 3D gain pattern of the slotted antenna

Table 3.2: Characteristics of the patch antenna with and without slots

	Fr (Hz)	S11 (dB)	Directivity (dBi)	Gain (dBi)
Unslotted antenna	3.49	-31.549	6.425	6.222
Slotted antenna	3.57	-27.5	6.546	6.492

Based on the results of the two antennas indicated in Table 3.2

- Increased Directivity: The integration of slots significantly increases the antenna's directivity compared to the conventional slotless design.
- Enhanced Gain: Due to the slotted structure, the antenna achieves a much higher gain than the one without slots.

3.3.4 Presentation of the patch antenna with slots and patch antenna array structure

In this section, a presentation of the single-element structure results will be provided, showing the antenna's characteristics both patch antenna with slots and patch antenna array.

- Patch antenna

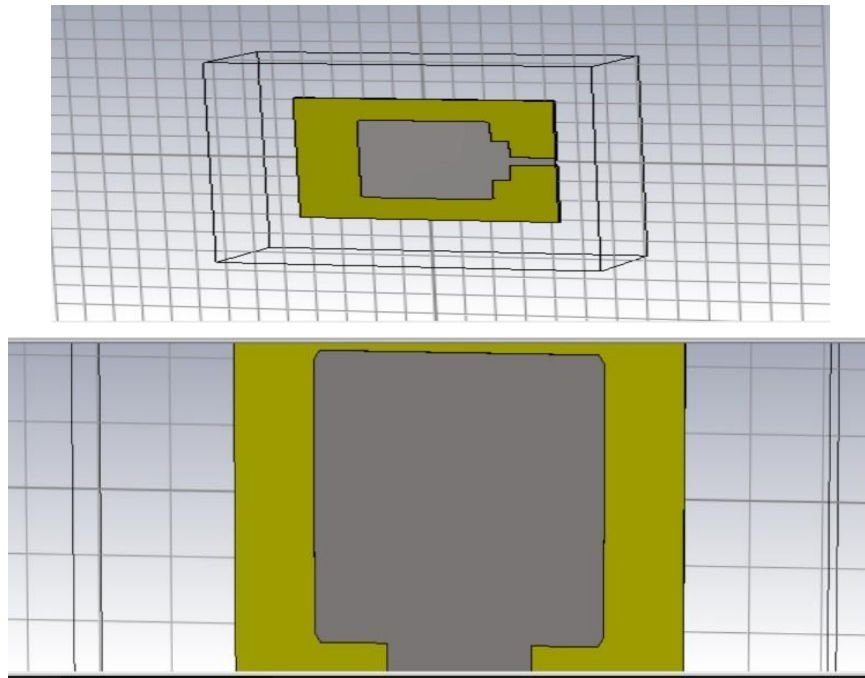


Figure 3.9. Patch antenna with slots

- Patch antenna array

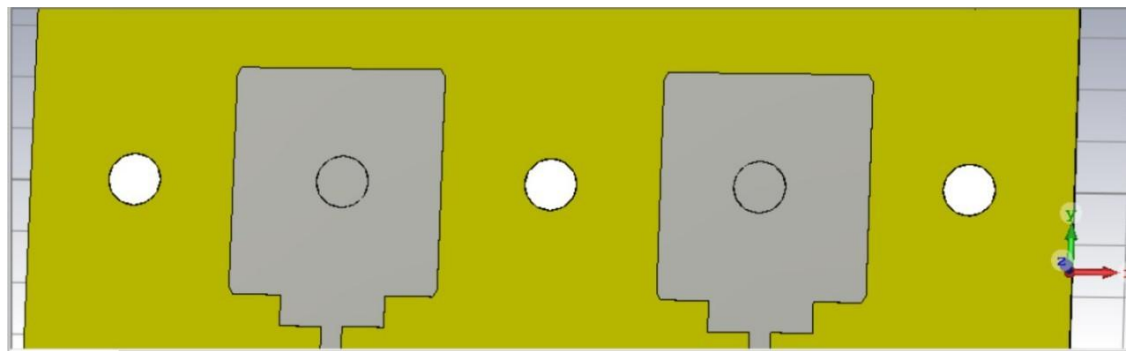
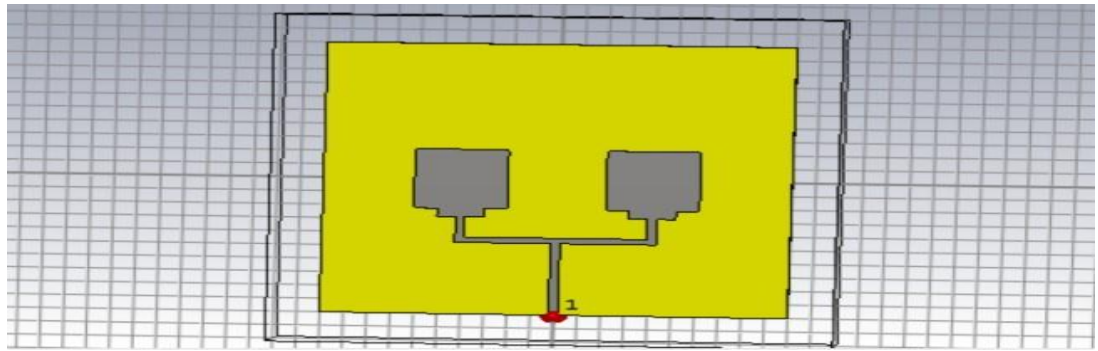


Figure 3.10. Patch antenna array

3.3.5 Comparison of patch antenna and patch antenna array

In this section, a comprehensive comparison between the single patch antenna and the patch antenna array will be presented to evaluate and analyze the performance differences.

A) Resonant frequency

- Patch antenna array

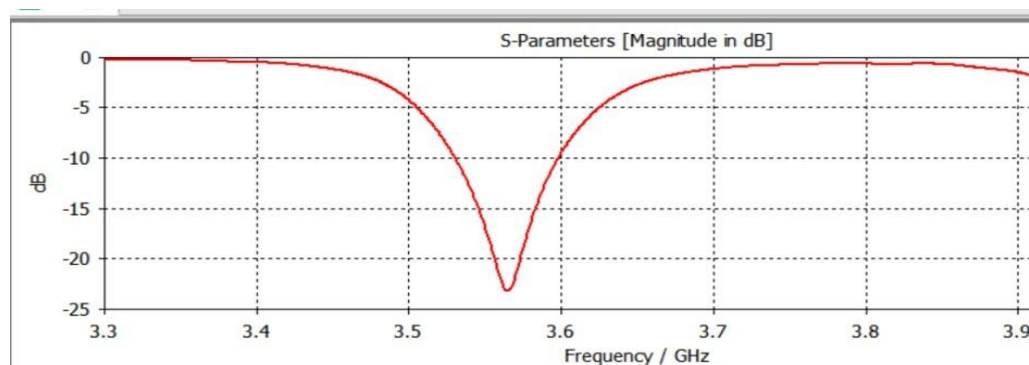


Figure 3.11. Reflection coefficient (S11) for the patch antenna array

- Patch antenna

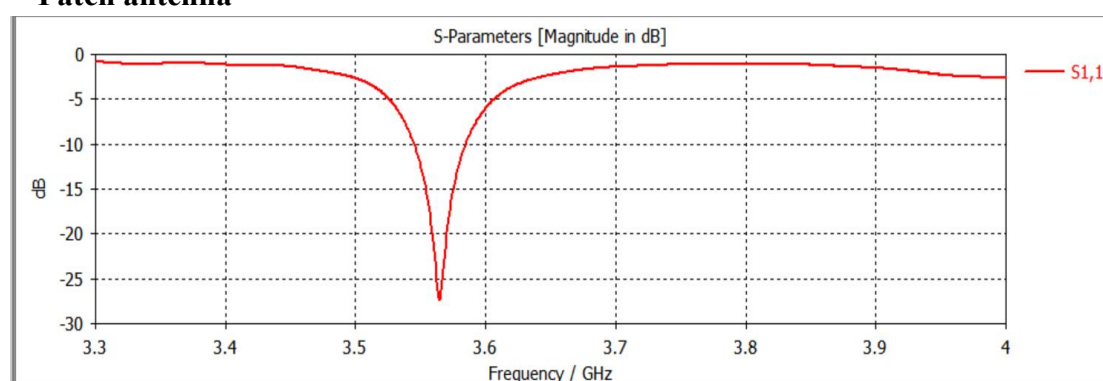


Figure 3.12. Reflection coefficient (S11) for the slotted patch antenna

A) Directivity (patch antenna and patch antenna array)

- Patch antenna array

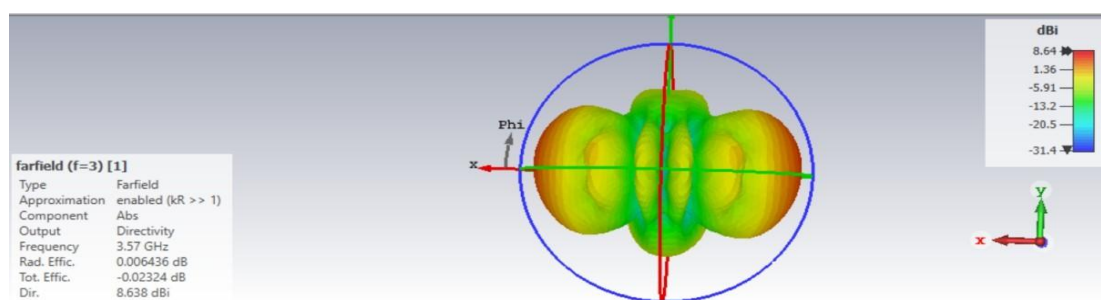


Figure 3.13. 3D directivity pattern of the patch antenna array

- Patch antenna

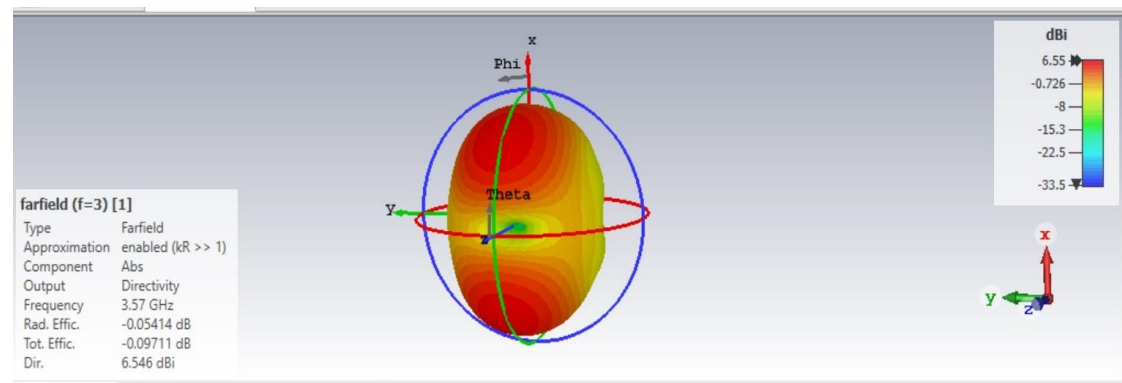


Figure 3.14. 3D directivity pattern of the patch antenna

B) Gain (patch antenna and patch antenna array)

- Patch antenna array

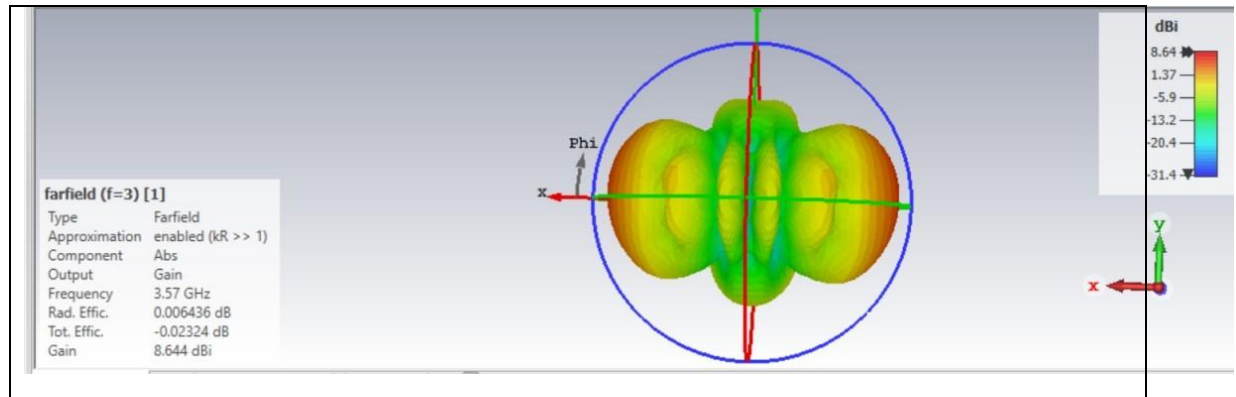


Figure 3.15. 3D gain pattern of the patch antenna array

- Patch antenna

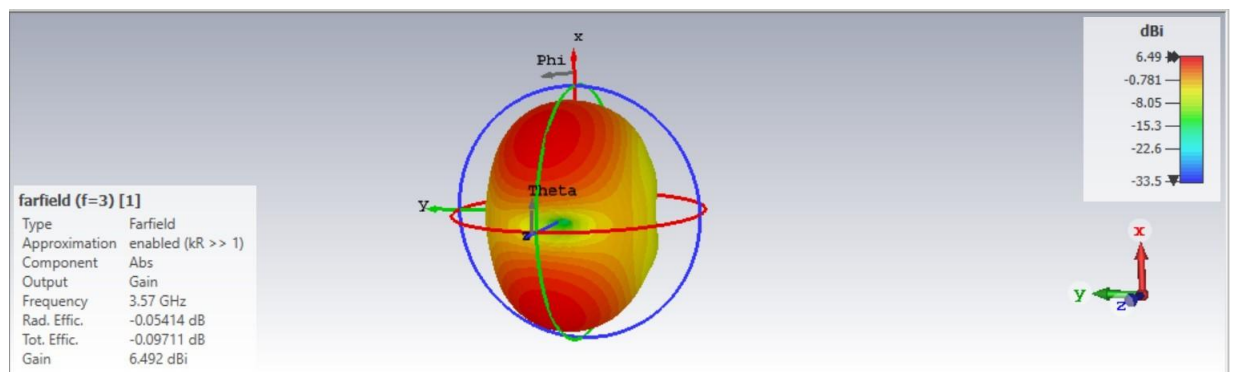


Figure 3.16. 3D gain pattern of the patch antenna

Table 3.3: Characteristics of the patch antenna and patch antenna array

	Fr (GHz)	S11(dB)	Directivity (dBi)	Gain (dBi)
Patch antenna	3.57	-30 .5	6.546	6.492
Patch antenna array	3.58	-23.5	8.638	8.644

Based on the results of the two antennas indicated in Table 3.3

- Directivity Enhancement : Employing the antenna array significantly increased the directivity compared to the single patch, indicating a more focused radiation beam.

- Gain Improvement : A noticeable enhancement in the antenna gain was achieved by shifting to the array configuration, which boosts the overall radiation efficiency.

3.3.6. Presentation of Patch antenna array structure with and without EBG

In this section, a presentation of the patch antenna array structure will be provided, showing the design both with and without EBG

- Patch antenna array

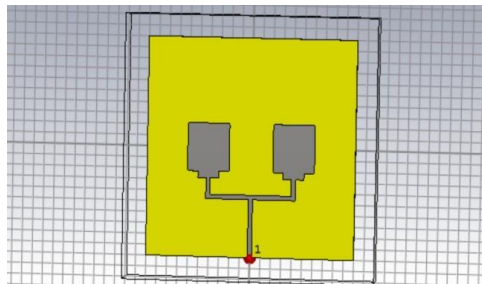
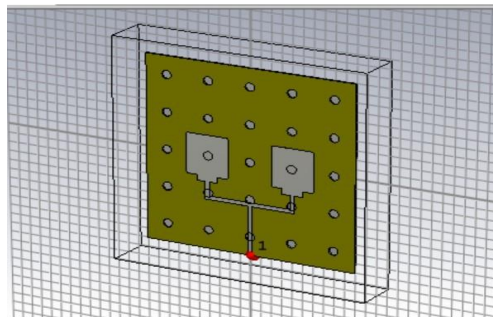


Figure 3.17. Patch antenna array without EBG



- Patch antenna array with EBG

Figure 3.18. Patch antenna array with EBG

3.3.7. Comparison of patch antenna array with and without EBG

In this section, a comprehensive performance comparison of the patch antenna array will be presented. We will compare and analyze the antenna's characteristics with EBG, and without EBG to evaluate their impact on the overall performance

A) Resonant frequency

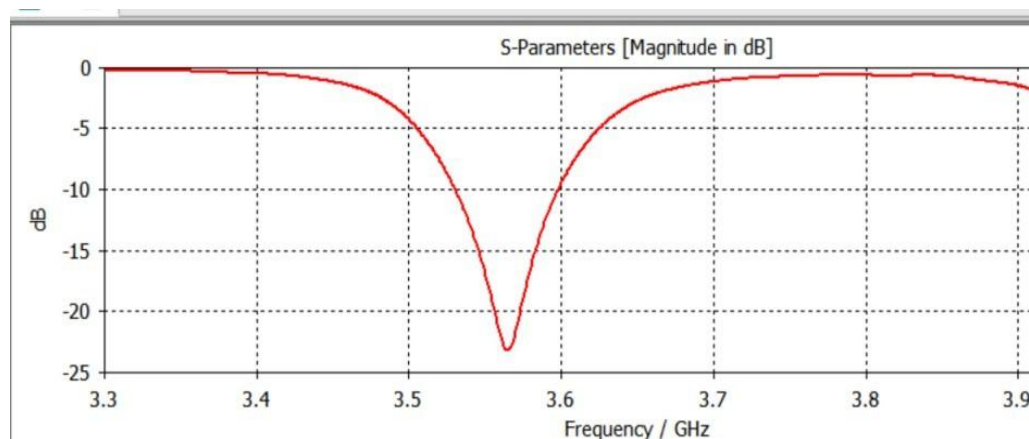


Figure 3.19. Reflection coefficient (S₁₁) for the patch antenna array without EBG

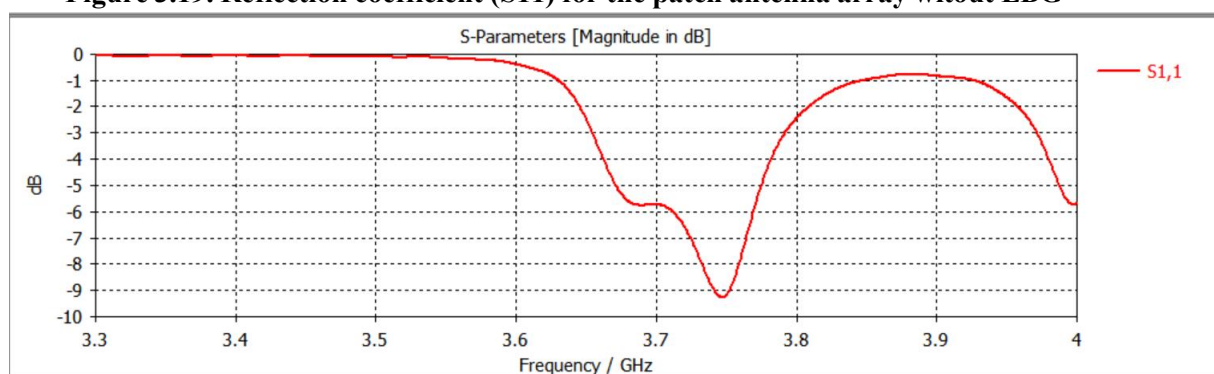


Figure 3.20. Reflection coefficient (S₁₁) for the patch antenna array with EBG

B) Directivity

- Patch antenna array

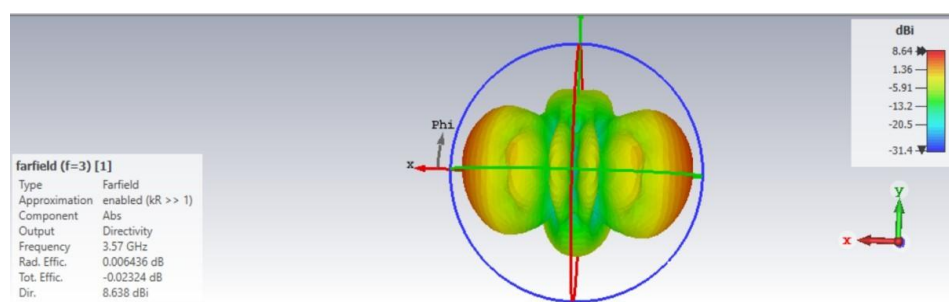


Figure 3.21. 3D directivity pattern of the patch antenna array without EBG

- Patch antenna array with EBG

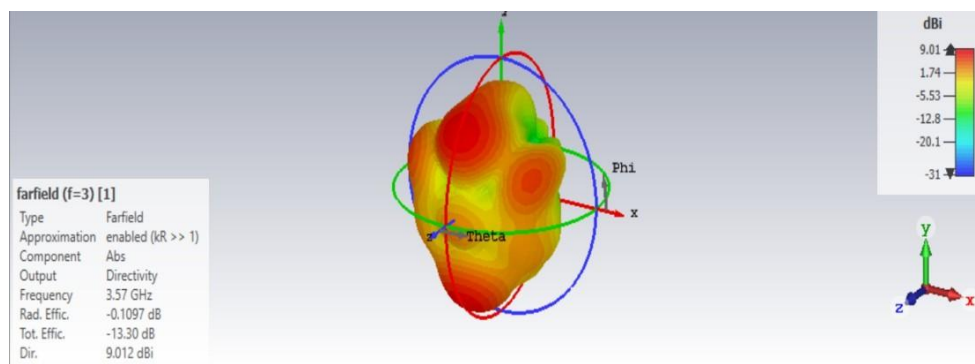


Figure 3.22. 3D directivity pattern of the patch antenna array with EBG

C) Gain

- Patch antenna array without EBG

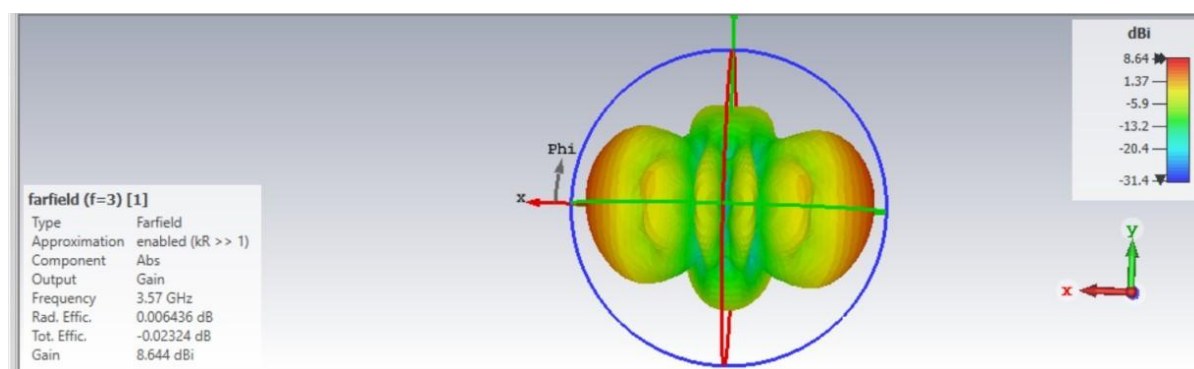


Figure 3.23. 3D gain pattern of the patch antenna array

- Patch antenna array with EBG

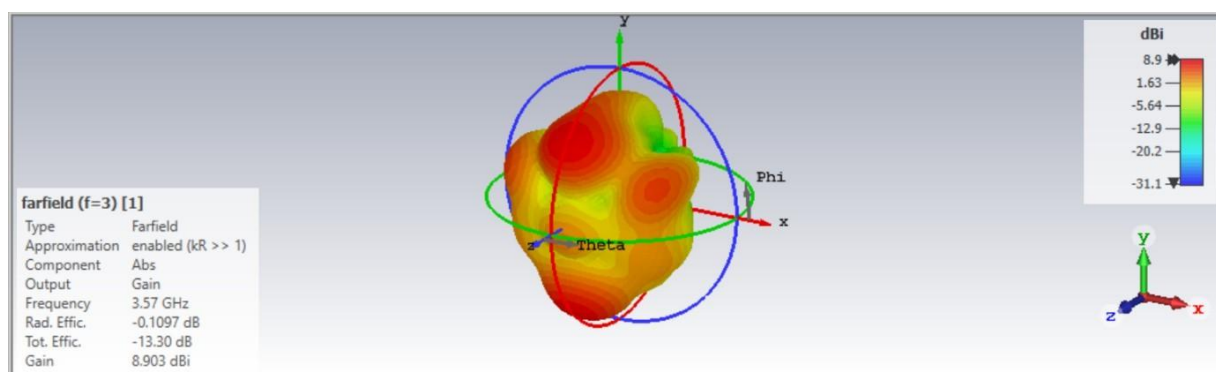


Figure 3.24. 3D gain pattern of the patch antenna array with EBG

Table 3.4: Characteristics of the patch antenna array with and without EBG

Patch antenna array	S11(db)	F(GHz)	BP(GHz)	Directivity (dBi)	Gain (dBi)
WIHOUT EBG	-23.5	0.0358	0.076	8.638	8.644
WITH EBG	-10.02	3.7466	0.0066861	9.012	8.903

Based on the results of the two antennas indicated in Table 3.4

- The gain and directivity for an antenna with EBG are improved by the suppression of surface waves and the resonant cavity effect

3.3.8. Effect of varying the substrate thickness of an EBG antenna

In this section, a presentation of the results regarding the effect of varying the substrate thickness of an EBG antenna will be provided, specifically focusing on its impact on the antenna's performance characteristics

A) Resonant frequency

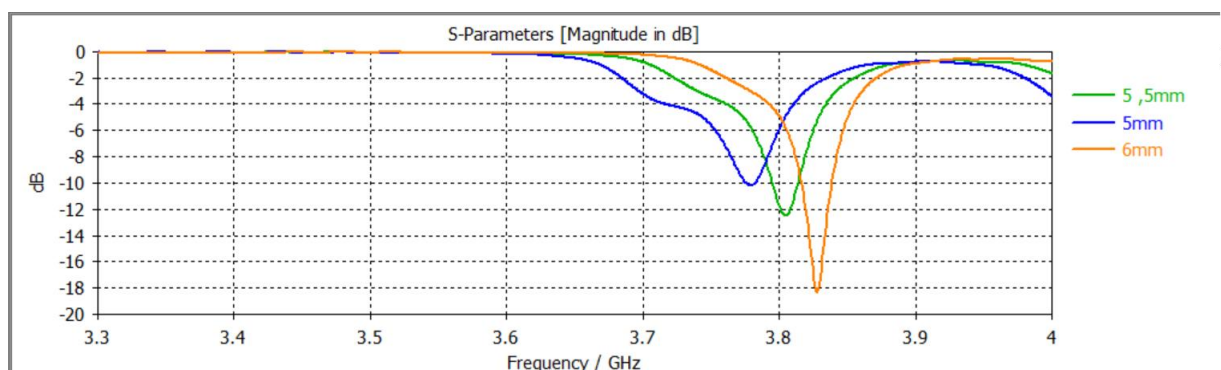


Figure 3.25. Reflection coefficient S11 for different substrate thicknesses

B) Directivity

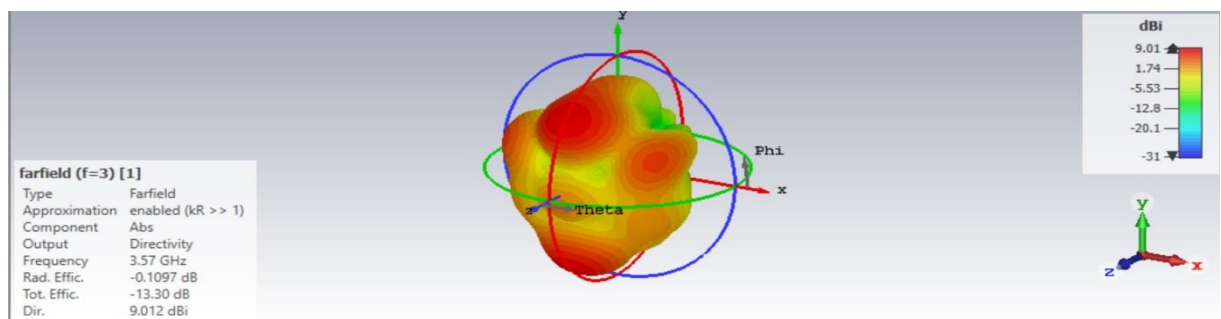


Figure 3.26. The 3D directivity for a substrate thickness of $h_1 = 5$ mm

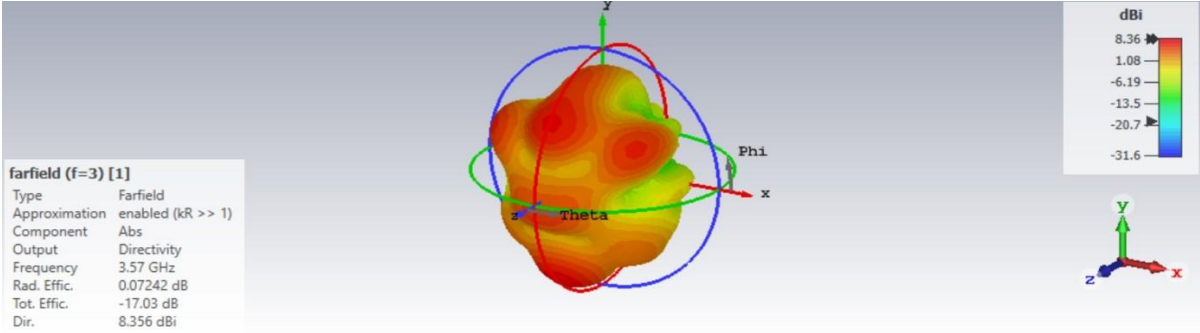


Figure 3.27. The 3D directivity for a substrate thickness of $h_1 = 5.5$ m

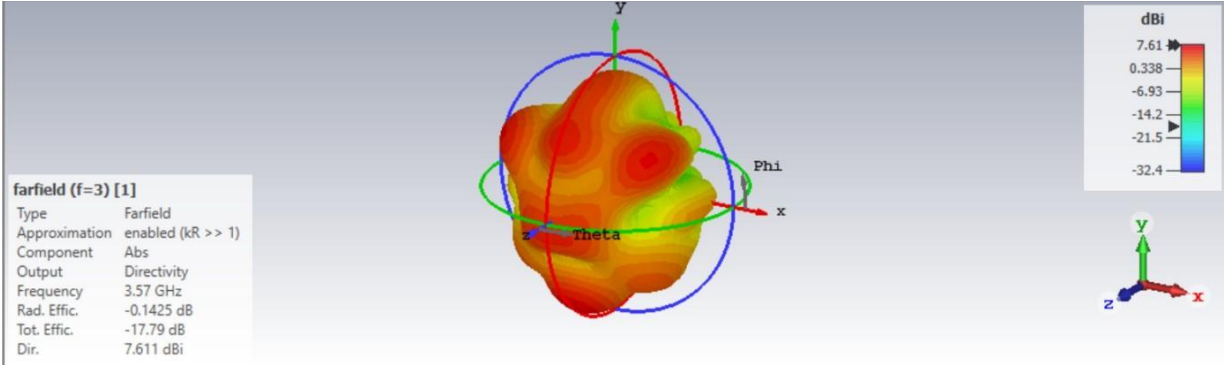


Figure 3.28. The 3D directivity for a substrate thickness of $h_1 = 6$ mm

C) Gain

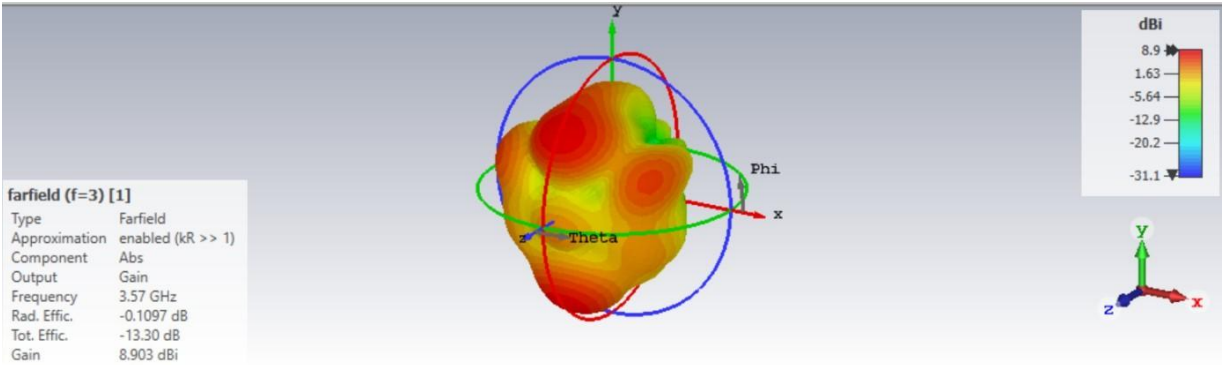


Figure 3.29. 3D gain for a substrate thickness of $h_1 = 5$ mm

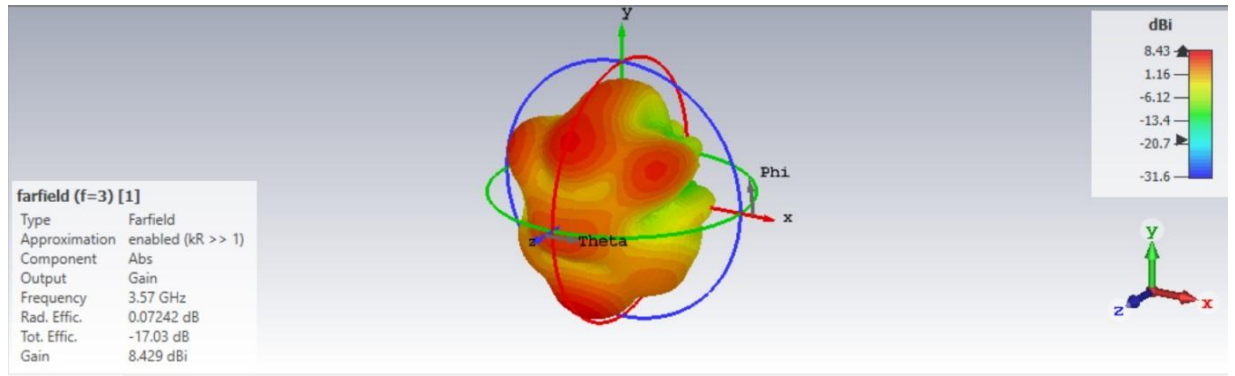


Figure 3.30. 3D gain for a substrate thickness of $h_1 = 5.5$ mm

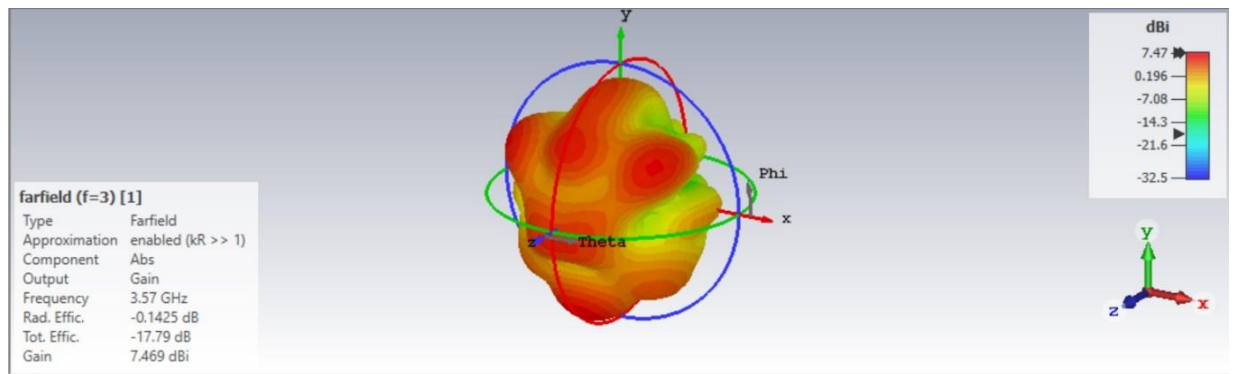


Figure 3.31. 3D gain for a substrate thickness of $h_1 = 6$ mm

Table 3.5: Characteristics of the slotted patch antenna as a function of substrate diameter

	F(GHz)	BP(GHz)	S11(db)	Directivity (dBi)	Gain (dBi)
d=5	3.7466	0.0066861	-10.02	9.012	8.903
d=5.5	3.8047	0.018826	-12.505	8.356	8.492
d=6	3.81	0.022244	-18.36	7.611	7.469

Based on the results of the two antennas indicated in Table 3.5

- The best antenna performance is obtained at EBG radius = 5 mm ;
- At 5 mm, the highest directivity and gain are achieved ;
- The S11 reflection coefficient varies with substrate thickness ;
- The S11 value is still acceptable while maintaining good matching ;
- The resonance frequency and directivity decrease as the substrate thickness increases ;
- The gain decreases with increasing substrate thickness.

3.3.9. Effect of Substrate Material Variation

In this section, a presentation of the results regarding the effect of substrate

material variation will be provided, specifically focusing on its impact on the antenna's performance characteristics

A) Resonant frequency

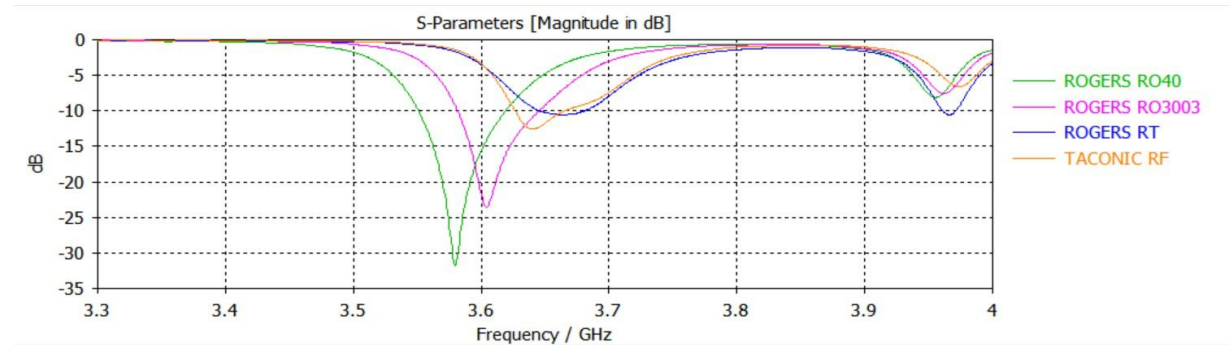


Figure 3.32: S11 reflection coefficient for the variation of the substrate material

B) Directivity

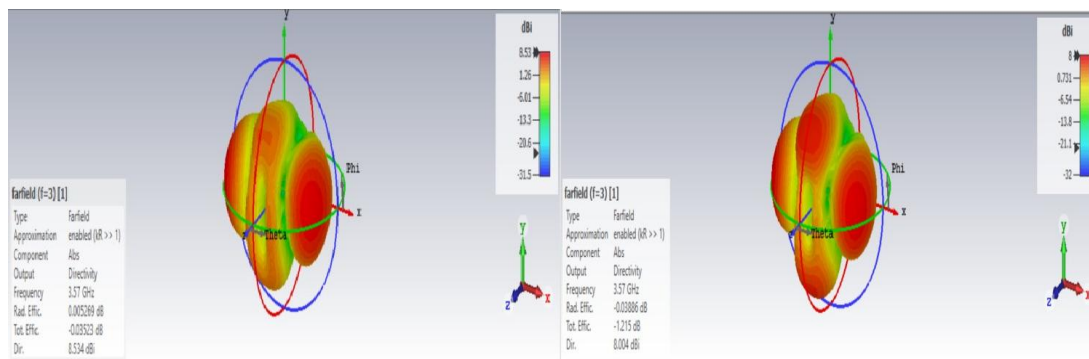


Figure 3.33. 3D directivity for (a) $\epsilon_r=3.83$ (b) $\epsilon_r=3.00$

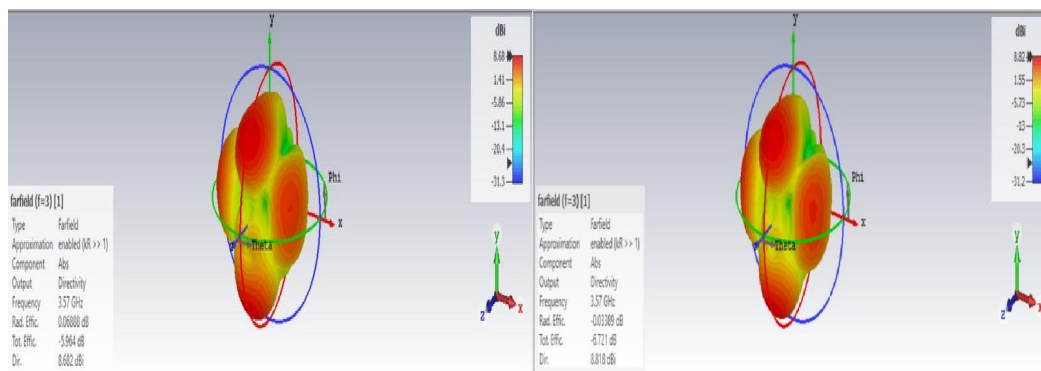


Figure 3.34. 3D directivity for (c) $\epsilon_r=2.20$ (d) $\epsilon_r=3.5$

C) Gain

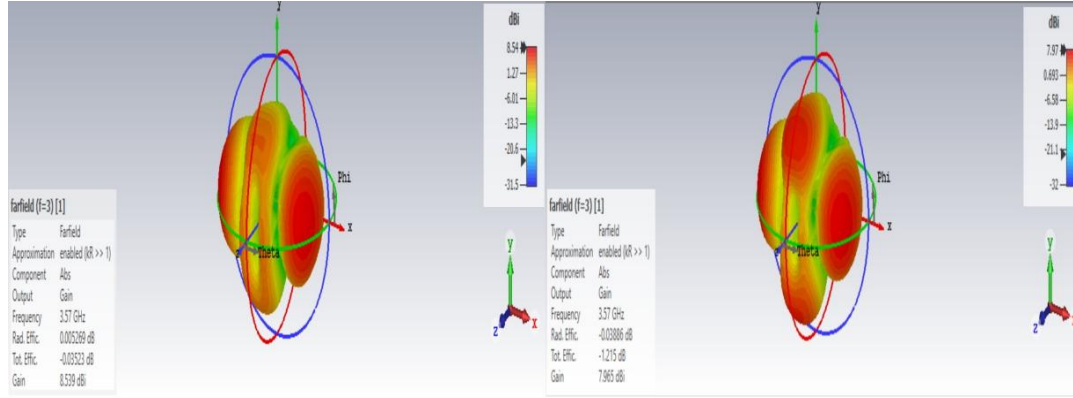


Figure 3.35. 3D Gain for (a) $\epsilon_r=3.83$ (b) $\epsilon_r=3.00$

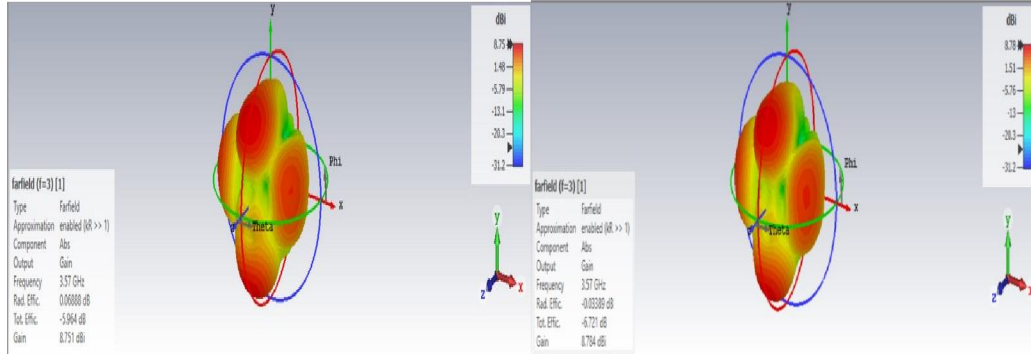


Figure 3.36. 3D Gain for (c) $\epsilon_r=2.20$ (d) $\epsilon_r=3.5$

Table 3.6: Characteristics of the EBG patch antenna as a function of substrate permittivity

	F(GHz)	BP(GHz)	S11(dB)	Directivity (dBi)	Gain (dBi)
$\epsilon_r=3.83$	3.5793	0.039211	-31.709	8.534	8.539
$\epsilon_r=3.00$	3.6045	0.0642	-23.545	8.004	7.965
$\epsilon_r=2.2$	3.664	0.0358	-10.557	8.682	8.751
$\epsilon_r=3.5$	3.640	0.068588	-12.592	8.818	8.784

Based on the results in Table 3.6 after varying the superstrate material, it can be observed that :

- Lower permittivity (ϵ_r) : Increases the resonant frequency.
- Higher permittivity (ϵ_r): Significantly improves the reflection coefficient (S11).
- Intermediate permittivity(ϵ_r): Yields the highest directivity and gain.

3.4. Effect of the FSS Layer

3.4.1. Frequency Selective Surface (FSS)

The FSS layer is a layer above the antenna patch that we described previously with a distance of $F= 13\text{mm}$ the patch, constituted of a group of patterns that we will present later.

Above them comes a layer called superstrate which is of the same length and width as the substrate and of different thickness.

3.4.2. How to simulate an FSS layer ?

Above the antenna patch that was created and at a distance of $F= 13\text{mm}$, we started with the first step, which consists of creating a pattern with its exact dimensions and overlapping shapes.

Then we added the final superstrate layer with the same dimensions as the substrate and the ground plane, taking into account a change in diameter of the motifs of superstrate and the distance between the patch and superstrate FSS to complete our FSS structure.

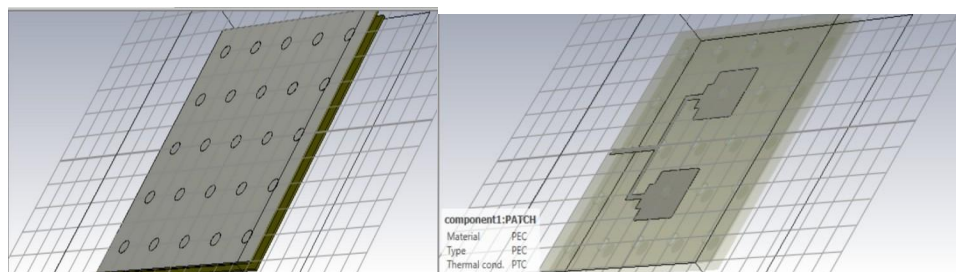


Figure 3.37. Patchantenna array with FSS

3.4.3. Comparison of patch antenna array with EBG and FSS and without FSS

In this section, a comprehensive performance comparison of the patch antenna array will be presented. We will compare and analyze the antenna's characteristics with EBG, with FSS, and without FSS to evaluate their impact on the overall performance

A) Resonant frequency

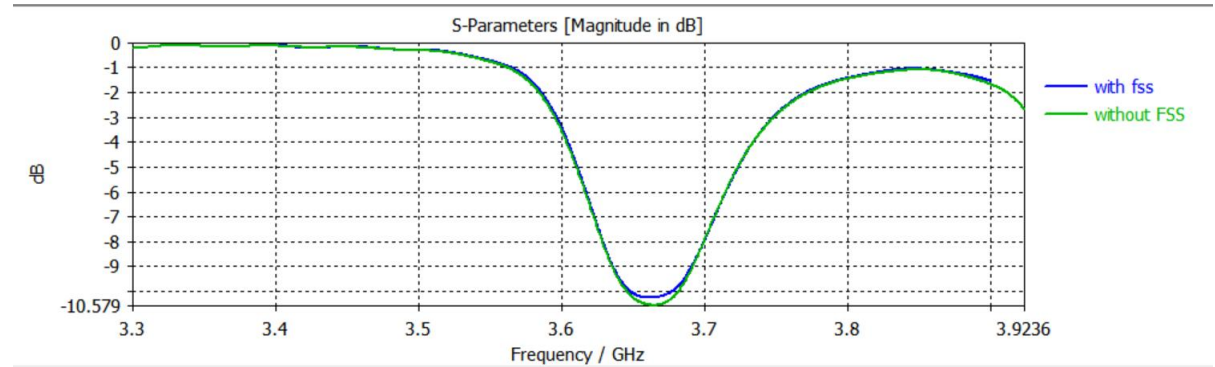


Figure 3.38. Patch Antenna array with EBG and FSS and without FSS

B) Directivity

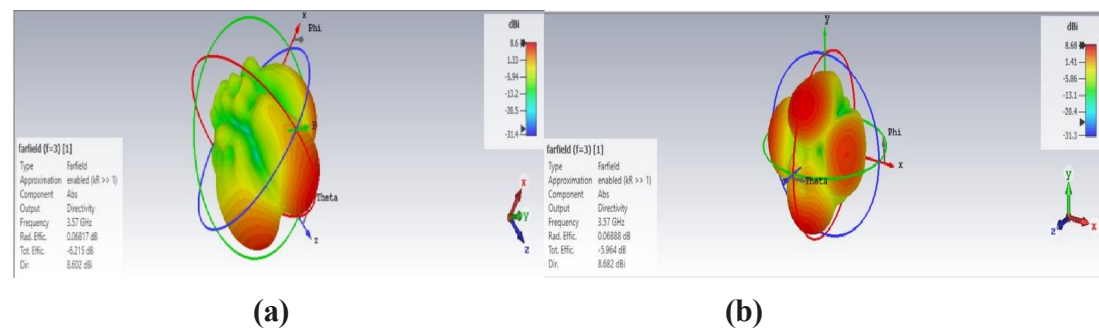


Figure 3.39. 3D directivity for patch antenna array with EBG and FSS, F= (a) and with just EBG (b)

C) Gain

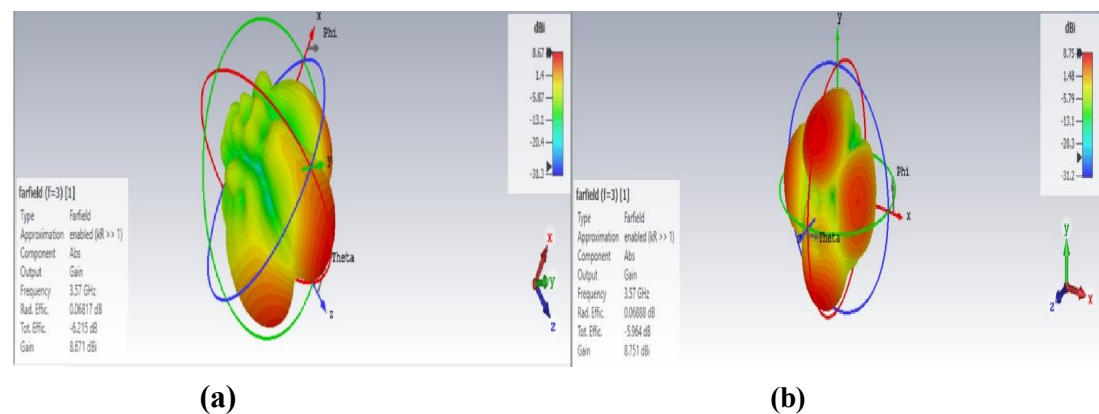


Figure 3.40. 3D gain for patch antenna array with EBG and FSS= (a) and with just EBG (b)

	S11 (db)	BP(GHz)	Directivity (dBi)	Gain (dBi)
With EBG	-10.557	0.03658	8.682	8.751
With EBG and FSS	-10.255	0.029039	8.602	8.671

Table 3.7. Characteristics of a patch antenna array with EBG and with EBG and FSS

After adding an FSS layer, we obtained an FSS patch antenna, and we compared it with the patch antenna with EBG.

- The directivity and gain showed a slight improvement for the EBG-FSS patch antenna compared to the design with EBG only
- The antenna without FSS is better matched than the antenna with FSS.
- The resonant frequency for the antenna with EBG and FSS decreased compared to the antenna with EBG only.

3.3.4 Effect of varying the diameter of the motifs of superstrat FSS

In this section, a presentation of the results regarding the effect of varying the diameter of the FSS motifs will be provided, specifically focusing on its impact on the antenna's performance characteristics

A) Resonant frequency

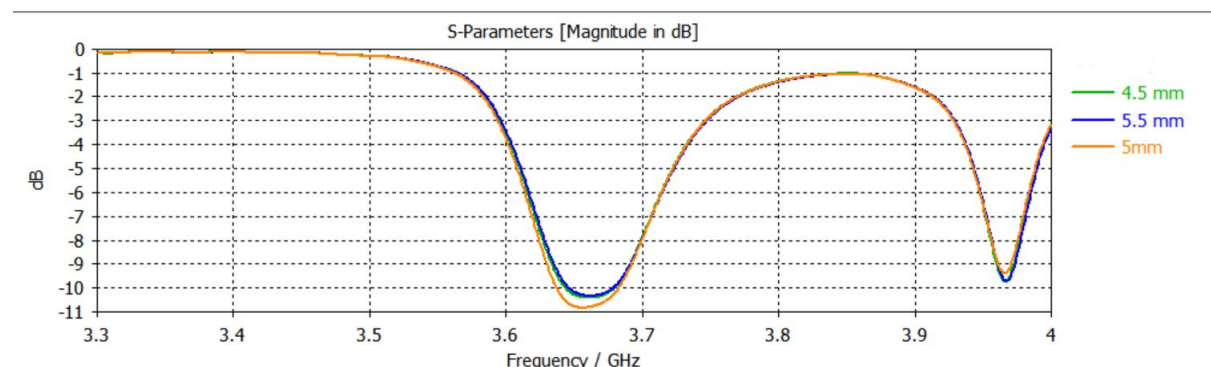


Figure 3.41. Reflection coefficients for different values of the diameter of the motifs of superstrat FSS

B) Directivity

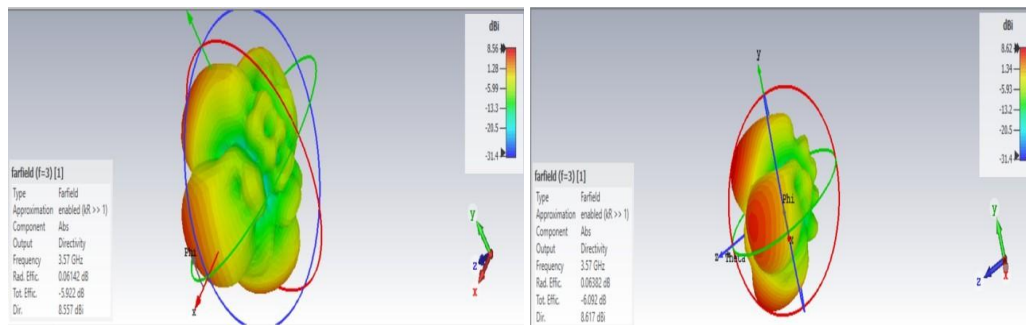


Figure 3.42. 3D directivities for the diameter (a) D= 4.5 mm (b) D= 5 mm

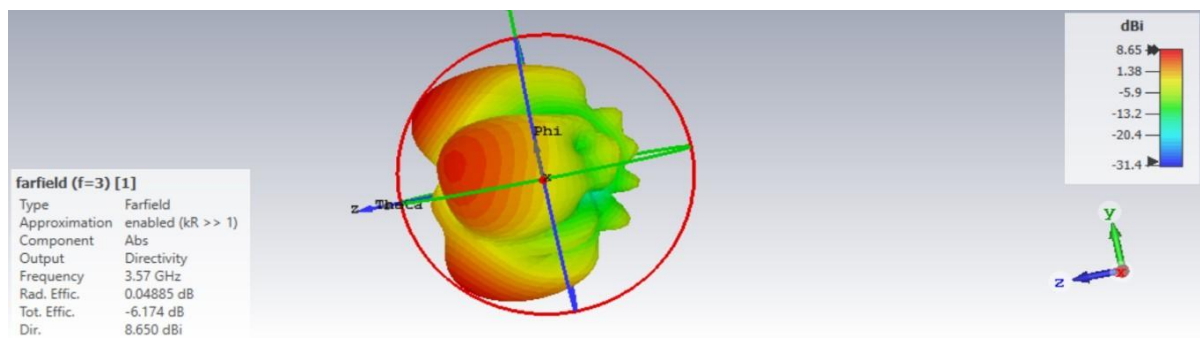


Figure 3.43. 3D directivities for the diameter (C) D= 5.5 mm

C) Gain

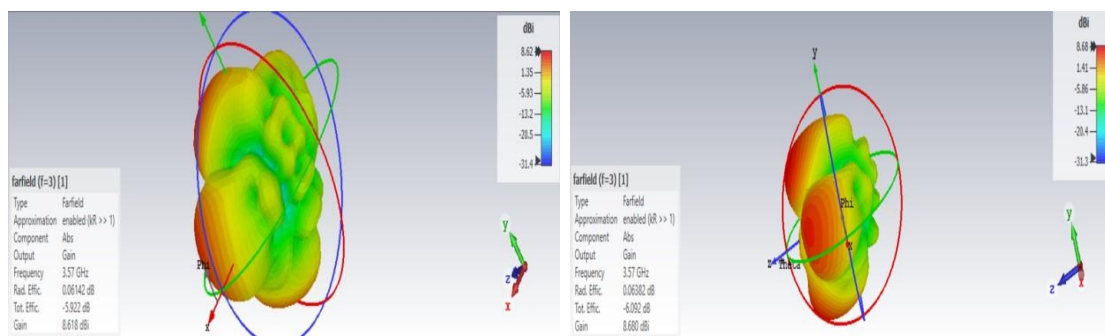


Figure 3.44. 3D gain for the diameter (a) D= 4.5 mm (b) D= 5 mm

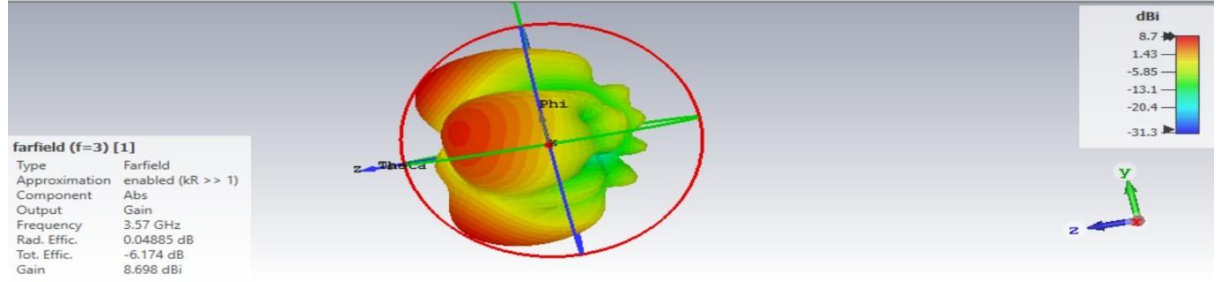


Figure 3.45. 3D gain for the diameter (c) $D = 5.5$ mm

Table 3.7. Characteristics of a patch antenna array with EBG and FSS for different values of the diameter

	F(GHz)	BP(GHz)	S11 (db)	Directivity (dBi)	Gain (dBi)
D=4.5mm	3.65	0.036755	-10.83	8.557	8.618
D=5mm	3.66	0.03678	-10.41	8.617	8.680
D=5.5mm	<u>3.66</u>	0.03269	-10.33	8.650	8.698

After changing the diameter, we extract :

- The best antenna performance is $D = 5.5$ mm ;
- At 5.5 mm, the highest directivity and gain are achieved ;
- The S11 value is still acceptable while maintaining good matching.

3.4.5. Effect of varying the distance between the patch and the superstrat FSS

In this section, a presentation of the results regarding the effect of varying the distance between the patch and the superstrat FSS will be provided, specifically focusing on its impact on the antenna's performance characteristics

A) Resonant frequency

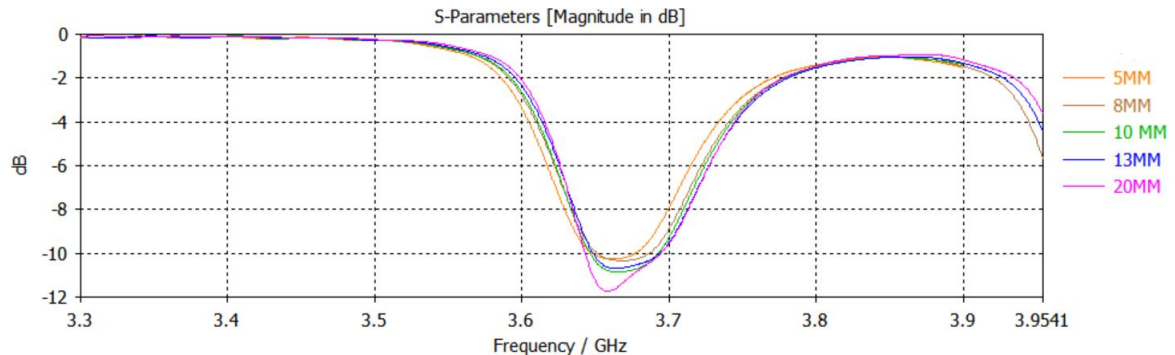


Figure 3.46. Reflection coefficients for different values of the distance.

B) Directivity

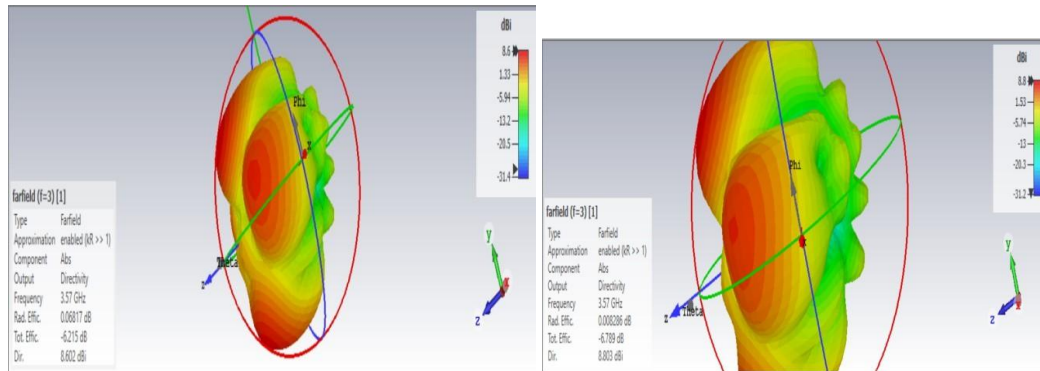


Figure 3.47. 3D directivities for the distance (a) $F = 5$ mm (b) $F = 8$ mm.

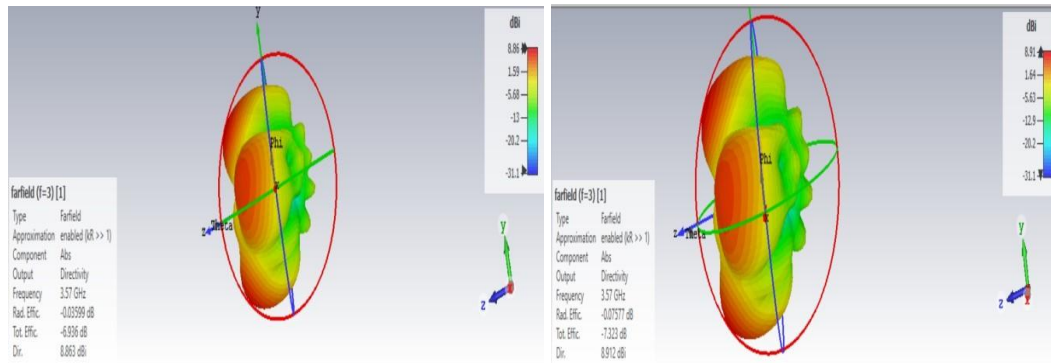


Figure 3.48. 3D directivities for the distance (C) $F = 10$ mm (D) $F = 13$ mm.

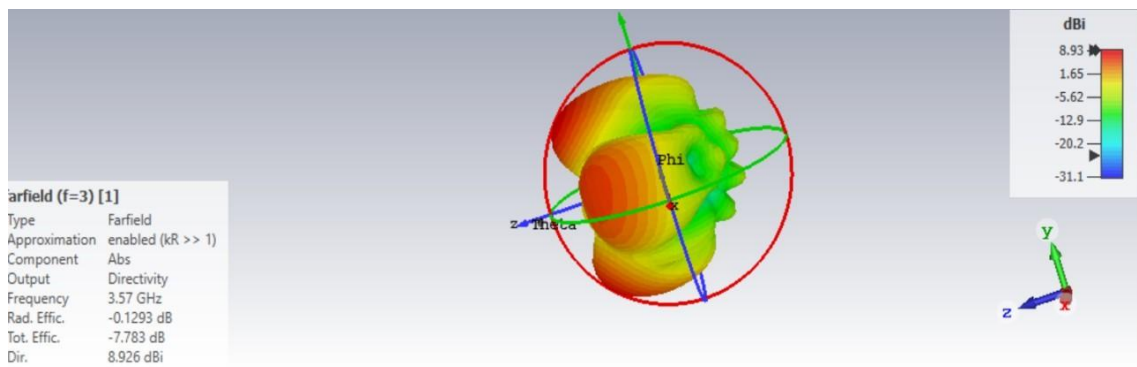


Figure 3.49. 3D directivities for the distance (e) $F = 20$ mm

C) Gain

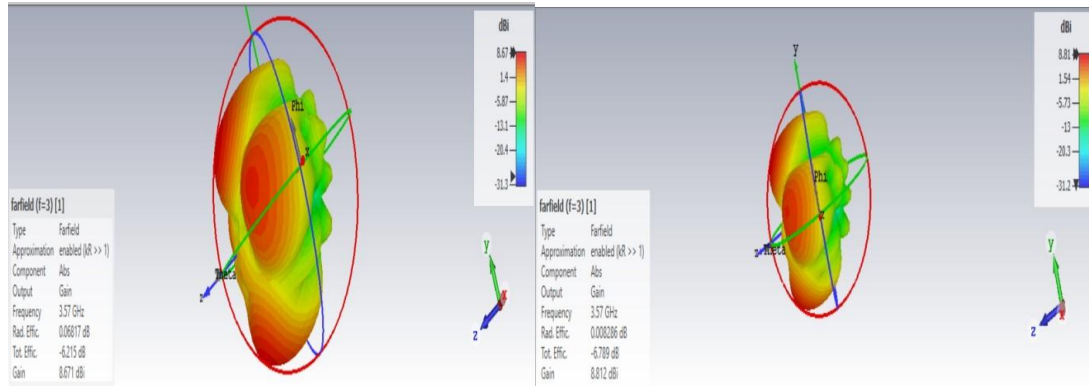


Figure 3.50. 3D Gain for the distance (a) $F = 5$ mm (b) $F = 8$ mm

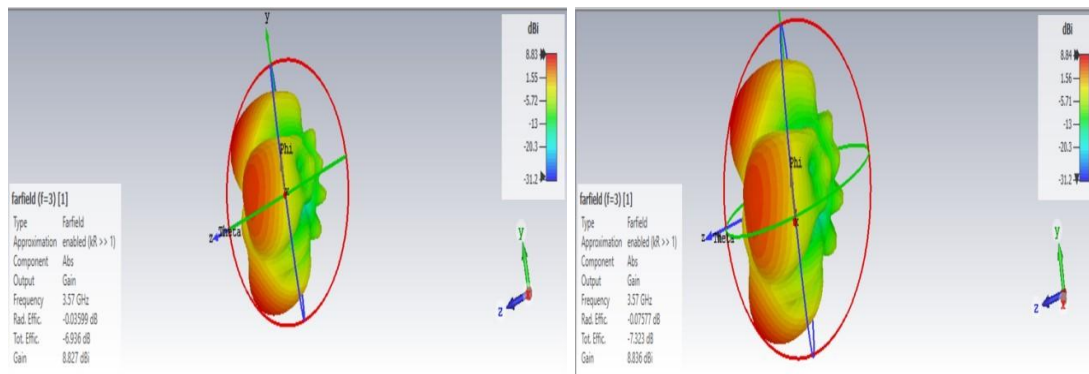


Figure 3.51. 3D gain for the distance (C) $F = 10$ mm (D) $F = 13$ mm.

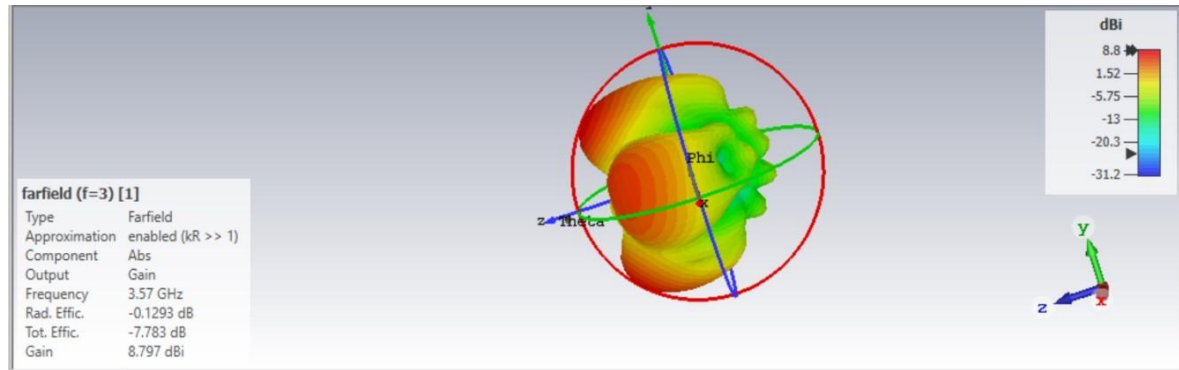


Figure 3.52. 3D gain for the distance (E) $F = 20$ mm

Table 3.8 Characteristics of The FSS-printed antenna as a function of the distance between the patch and the FSS

	F(GHz)	BP(GHz)	S11(db)	Directivity (dBi)	Gain (dBi)
F=5	3.662	0.029039	-10.25	8.602	8.671
F=8	3.678	0.035765	-10.33	8.803	8.812
F=10	3.664	0.047053	-10.85	8.863	8.827
F=13	3.663	0.046124	-10.69	8.912	8.836

F=20	3.658	0.05168	-11.73	8.926	8.797
------	-------	---------	--------	-------	-------

Après le changement de la distance F on extrait

- A clear improvement in gain and directivity is achieved by increasing the distance
- A clear improvement in the impedance matching S_{11} is achieved by increasing the distance

Conclusion

In conclusion, this chapter has presented the performance of an EBG patch antenna operating in the 3.5 GHz band designated for 5G applications. Through a series of numerical simulations, the focus was placed on the presentation of how varying the substrate permittivity impacts the antenna's characteristic parameters, including the resonant frequency, reflection coefficient (S_{11}), directivity, and gain. The obtained results demonstrate that a careful selection of the substrate material allows for the precise tuning of the radiation performance. Utilizing an intermediate permittivity optimized both gain and directivity, while higher permittivity values enhanced the impedance matching (S_{11}). These initial findings pave the way for the next phase of our study, which will focus on deploying more advanced configurations to further enhance the overall system performance.

General Conclusion

General Conclusion

In conclusion, the relentless evolution of 5G wireless communication systems has driven an unprecedented demand for compact, highly efficient, and high-performance antennas capable of thriving in the demanding microwave and millimeter-wave spectrums. Among various configurations, microstrip patch antennas remain a highly practical and foundational choice owing to their low profile, cost-effectiveness, ease of fabrication, and seamless compatibility with modern monolithic integrated communication modules.

This work has comprehensively highlighted the transformative role of metamaterial-inspired elements, specifically Electromagnetic Band Gap (EBG) and Frequency Selective Surface (FSS) configurations, in overcoming the severe inherent physical constraints of conventional patch antennas—most notably their narrow bandwidth and surface wave losses. By artificially manipulating electromagnetic wave propagation, eliminating surface wave modes, and suppressing mutual coupling, these periodic structures have proven essential in significantly boosting radiation efficiency, gain, and overall antenna directivity.

A pivotal contribution of this thesis was executed through intensive parametric optimizations and design iterations. By implementing critical structural adjustments on the unit cell dimensions, lattice periodicities, substrate profiles, and feeding mechanisms, we successfully mitigated severe impedance mismatches. The electromagnetic simulations, carried out via CST Microwave Studio, provided rigorous validations of these enhancements. The compiled results demonstrate a remarkable improvement in the reflection coefficient (S_{11}), a precise stability at the target resonant frequency, and a substantial expansion of the operational bandwidth.

Ultimately, the empirical and simulated outcomes validated that integrating optimized EBG and FSS structures directly into the antenna architecture successfully resolves the trade-off between miniaturization and performance. The strategic changes and fine-

General conclusion

tuning conducted throughout the design phases yielded an exceptional impedance matching and structural adaptation. Consequently, the convergence of microstrip patch technology and advanced periodic metamaterials stands as a highly promising, reliable, and scalable paradigm for the deployment of next-generation 5G millimeter-wave architectures and future wireless networks

Bibliographie

- [1] C. A. Balanis, *Antenna Theory : Analysis and Design*, 3rd ed., Wiley, 2005.
- [2] R. Garg et al., *Microstrip Antenna Design Handbook*, Artech House, 2001.
- [3] D. M. Pozar, *Microwave Engineering*, 4th ed., Wiley, 2011.
- [4] K. L. Wong, *Compact and Broadband Microstrip Antennas*, Wiley, 2002.
- [5] R. Waterhouse, *Printed Antennas for Wireless Communications*, Wiley, 2007.
- [6] ITU-R, *Recommendation M.2083: IMT Vision – Framework and overall objectives of the future development of IMT for 2020 and beyond*, International Telecommunication Union, 2015.
- [7] Ericsson, *The 5G Business Potential*, White Paper, 2021.
- [8] Qualcomm, *5G Vision: Enabling the Next Generation of Connectivity*, Technical Report, 2020.
- [9] Nokia, *The Evolution to 5G and Beyond*, White Paper, 2019.
- [10] GSMA, *5G Spectrum Positions*, Report, 2021.
- [11] European 5G Observatory, *5G Spectrum Assignments in Europe*, European Commission, 2022.
- [12] 3GPP, *Release 15 and 16: 5G System Specifications*, Technical Specification, 2020.
- [13] Ericsson, *5G Millimeter Wave Technology Overview*, Technical Report, 2020.

Bibliographie

- [14] T. S. Rappaport et al., *Millimeter Wave Wireless Communications*, Pearson/Prentice Hall, 2014.
- [15] A. Goldsmith, *Wireless Communications*, Cambridge University Press, 2005.
- [16] 3GPP, *Release 15: 5G NR Specifications, Technical Specification*, 2019.
- [17] 3GPP, *5G NR System Architecture and Specifications (Release 15/16)*, 2019–2020.
- [18] Ericsson, *5G and Beyond: Enabling High-Capacity Networks, White Paper*, 2021.
- [19] Ericsson, *5G Use Cases and Applications Overview, White Paper*, 2021.
- [20] T. S. Rappaport et al., *Millimeter Wave Wireless Communications*, Pearson, 2014.
- [21] ITU, *IMT-2020 Applications and IoT Connectivity Report*, 2020.
- [22] 3GPP, *Vehicle-to-Everything (V2X) Communications in 5G, Technical Report*, 2019.
- [23] N. Engheta and R. W. Ziolkowski, *Metamaterials: Physics and Engineering Explorations*, Wiley, 2006.
- [24] V. G. Veselago, “The Electrodynamics of Substances with Simultaneously Negative ϵ and μ ,” *Soviet Physics Uspekhi*, 1968.
- [25] D. R. Smith et al., “Composite Medium with Simultaneously Negative Permeability and Permittivity,” *Physical Review Letters*, 2000.
- [26] B. A. Munk, *Frequency Selective Surfaces: Theory and Design*, Wiley, 2000.
- [27] R. Mittra et al., “Techniques for Analyzing Frequency Selective Surfaces,” *Proceedings of the IEEE*, 1988.
- [28] J. D. Joannopoulos et al., *Photonic Crystals: Molding the Flow of Light*, Princeton Univ. Press, 1995.

Bibliographie

- [29] F. Yang and Y. Rahmat-Samii, *Electromagnetic Band Gap Structures in Antenna Engineering*, Cambridge, 2009.
- [30] W. L. Bragg, "The Reflection of X-rays by Crystals," 1915.
- [31] E. Yablonovitch, "Inhibited Spontaneous Emission in Solid-State Physics and Electronics," *Physical Review Letters*, 1987.
- [32] S. John, "Strong Localization of Photons in Certain Disordered Dielectric Superlattices," *Physical Review Letters*, 1987.
- [33] K. M. Ho et al., "Existence of a Photonic Gap in Periodic Dielectric Structures," *Physical Review Letters*, 1990.
- [34] T. F. Krauss, "Slow Light in Photonic Crystal Waveguides," *Journal of Physics D*, 2007.
- [35] D. Sievenpiper et al., "High-Impedance Electromagnetic Surfaces," *IEEE Transactions on Microwave Theory and Techniques*, 1999.
- [36] J. B. Pendry et al., "Magnetic Response of Metamaterials Using Split-Ring Resonators," *IEEE Transactions on Microwave Theory and Techniques*, 1999.
- [37] D. M. Pozar, *Microwave Engineering*, 4th ed., Wiley, 2011.
- [38] J. D. Kraus, *Electromagnetics*, McGraw-Hill, 1991.
- [39] C. L. Holloway et al., "Applications of FSS in Radomes," *IEEE Antennas and Propagation Magazine*, 2003.
- [40] C. A. Balanis, *Antenna Theory: Analysis and Design*, 3rd ed., Wiley, 2005.
- [41] J. C. Knight et al., "All-Silica Single-Mode Optical Fiber with Photonic Crystal Cladding," *Optics Letters*, 1996.
- [42] P. Russell, "Photonic Crystal Fibers," *Science*, 2003.
- [43] T. A. Birks et al., "Endlessly Single-Mode Photonic Crystal Fiber," *Optics Letters*, 1997.
- [44] D. Labilloy et al., "Quantitative Measurement of Photonic Band Gap in a Two-Dimensional Photonic Crystal InP-Based Structure," *Physical Review Letters*, 1997.

- [45] A. Mekis et al., “High Transmission through Sharp Bends in Photonic Crystal Waveguides,” *Physical Review Letters*, 1996.
- [46] S. G. Johnson et al., “Linear Waveguides in Photonic Crystal Slabs,” *Physical Review E*, 2000.
- [47] S. Fan et al., “Channel Drop Filters in Photonic Crystals,” *Optics Express*, 1998.
- [48] E. R. Brown et al., “Radiation Properties of a Planar Antenna on a Photonic-Crystal Substrate,” *Journal of the Optical Society of America B*, 1993.
- [49] D. Sievenpiper et al., “High-Impedance Electromagnetic Surfaces,” *IEEE Trans. MTT*, 1999.
- [50] M. Agio et al., “Efficiency Improvement of Antennas on Ultra-Refractive Photonic Crystals,” *IEEE AP-S*, 2001.
- [51] M. Thurai et al., “Periodic Materials for Antennas and Propagation,” *IEE Proceedings*, 2002.
- [52] T. J. Cui et al., *Metamaterials: Theory, Design, and Applications*, Springer, 2010.
- [53] S. Maci et al., “Metasurfaces in Electromagnetics Mercedes,” *IEEE Antennas and Propagation Magazine*, 2011.

General conclusion

General conclusion

Bibliographie