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Thème

High performance metamaterial based microstrip antenna

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To my dear parents,

No homage could match the love you keep filling me with. That you find in this report a testimony of my love.

May God give you a long life.

To my dear brothers and sisters Mohammed, Chabane, Sekoura and Kahina whom I love deeply,

To my mates for their understanding and the moral support and encouragement they have given me. May this work be the expression of my deep affection.

To my buddy and my dear friend Soulef

To my teachers, for their efforts.

To all those who have been able to bring me help and support at the right times, and point me in the right direction by reminding me that will makes great people.

May they find my sincere gratitude here.

Omar.

Dedications

To my dear parents,

No homage could match the love you keep filling me with. That you find in this report a testimony of my love.

May God give you a long life.

To my dear brother and sister, Idriss and Souad whom I love deeply,

To my friends for their understanding and the moral support and encouragement they have given me. May this work be the expression of my deep affection.

To my buddy and my dear friend Omar

To my teachers, for their efforts.

To all those who have been able to bring me help and support at the right times, and point me in the right direction by reminding me that will makes great people.

May they find my sincere gratitude here.

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ملخص

لقد أصبح من الضروري إيجاد حلول جديدة لتلبية الأداء العالي للهوائيات، لذلك تم اقتراح تصميم جديد لهوائي التصحيح متعدد الموجات Microstrip للحصول على عروض نطاق متعددة تغطي نطاقات تردد مختلفة ل X. و WLAN. يتم حفر الهوائي على ركيزة $FR4$ مع وحدة التغذية $50\ \Omega$. تحتوي الرقعة المستطيلة على قطعة مستديرة في كل زاوية مع فتحة واحدة في المستوى الأرضي. يتم إدخال U أو H معكوسة أو U مقلوبة في الرقعة مما يعطي سلوكًا يمكن رؤيته على أنه نطاق عريض ثنائي، وتوفر فتحة أخرى H ثلاثة أشرطة عريضة. ثم تقارن هوائيات بالMetamaterials بنفس المعلومات مع الهوائيات المعدنية، فتعطي أداءً عاليًا. تتم المحاكاة باستخدام برنامج HFSS وترسم البيانات باستخدام برنامج ORIGIN.

الكلمات الدالة: التصحيح، HFSS، المواد الخام، متعدد الفتحات، متعدد النطاقات الواسعة، UWB.

Abstract

It has become essential to find new solutions to satisfy high performances for antennas, for that a new design of Multiband Microstrip patch antenna is proposed to satisfy multi-wide-bandwidths covering different frequency ranges for WLAN and X-bands. The antenna is etched on $FR4 - substrate$ with $50\ \Omega$ feed line. The patch has one round cut at each corner with one slot in the ground plane and an insertion of U, inversed H or inversed U slot in the patch which gives behavior of bi-wide-bands, and an H-slot offers three-wide-bands. Then a metamaterial antenna with the same parameters is compared by the metallic antennas, it gives high performances. The simulation is carried out using the simulation software HFSS and graphs are plotted using the software ORIGIN.

Keywords: Patch, HFSS, Metamaterials, Multislot, Multi-wide-band, UWB.

Résumé

Il est devenu essentiel de trouver des solutions pour satisfaire des antennes à hautes performances, pour cela une nouvelle conception d'une antenne patch multi-bandes micro-ruban est proposée pour satisfaire multiples bandes couvrant différentes gammes de fréquences pour les bandes $WLAN\ et\ X$. L'antenne est gravée sur un substrat $FR4$ avec une ligne d'alimentation de $50\ \Omega$. Le patch a une coupe ronde dans chaque coin avec une fente dans le plan de masse, des fentes sous forme U, H inversée ou U inversée dans le patch donnent double-larges bandes, un H offre trois larges bandes. Ensuite, une antenne a métamatériaux avec les mêmes paramètres est comparée par les métalliques, elle donne des performances plus élevées. La simulation est réalisée par le logiciel HFSS et les graphes sont tracés par ORIGIN.

Mots clés : Patch, HFSS, Métamatériaux, Multislot, multi-large bande, ULB.

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BW (**Bandwidth**) : is the difference between the upper and lower frequencies in a continuous band of frequencies. Typically measured in hertz.
EBG (Electromagnetic Band Gap): a structure that creates a stopband to block electromagnetic waves of certain frequency bands by forming a fine, periodic pattern of small metal patches on dielectric substrates.
EM (Electromagnetic) : phenomena which includes both electricity and magnetism as different manifestations of the same phenomenon.
FCC (Federal Communications Commission) regulates interstate and international communications by radio, television, wire, satellite, and cable in all 50 states, the District of Columbia and U.S. territories.
FSS (The frequency selective surfaces): any thin, repetitive surface (such as the screen on a microwave oven) designed to reflect, transmit or absorb electromagnetic fields based on the frequency of the field.
MIMO (Multiple-Input Multiple-Output): A multiplexing technique used in radars, wireless networks and mobile networks allowing data transfers at longer range and with higher speed.
MTMs (Metamaterials): an artificial composite material that has electromagnetic properties not found in natural material.
NRI (**Negative refractive index)**
RFID (Radio frequency): an electromagnetic wave frequency between 3 kHz and 300 GHz (between 3 × 103 and 3 × 1011 Hz), which includes the frequencies used by different radiocommunication means.
ROS **(Stationary Wave Report) :** the ratio of its instantaneous amplitude at one point to that at any other point does not vary with time.
SRR (Split Ring Resonator): An artificially produced structure common to metamaterials. Their purpose is to produce the desired magnetic susceptibility (magnetic response) in various types of metamaterials up to 200 terahertz.
TLM (The transmission line matrix) : a space and time discretizing method for computation of electromagnetic fields.
UWB (Ultra-Wide Band): The bandwidth can reach very high values
WB (Wide Band): The bandwidth can reach high values

Table of abbreviations

WLAN (Wireless Local Area Network): a wireless distribution method for two or more devices that use high-frequency radio waves and often include an access point to the Internet.

LIST OF SYMBOLS

$fres$ (**Resonance frequency**) : a phenomenon according to which certain physical systems (electrical, mechanical ...) are sensitive to certain frequencies.

G **(Gain)** : The gain generally expressed in decibels expresses the ability of an antenna to transmit more than a reference antenna in a given direction.

$S11$ **(Reflection coefficient):** a parameter that describes how much of a wave is reflected by an impedance discontinuity in the transmission medium.

c (Speed of light)

D **(Directivity)** : a parameter of an antenna or optical system which measures the degree to which the radiation emitted is concentrated in a single direction.

Pt **(Total transmitted power)** : the sum of the carrier power and the sideband power.

PA **(Power of an antenna)** : a measure of how much power is radiated by an antenna.

PN **(Noise power)** : Any unwanted input - UNDESIRABLE portion of an electrical signal Limits systems ability to process weak signals.

PR **(Radiated power)** : an IEEE standardized definition of directional radio frequency (RF) power, such as that emitted by a radio transmitter.

General introduction

With the rapid growth of the wireless mobile communication technology, the need of the wide band and multi band antennas is increased to serve various wireless technologies using different frequencies, for that it has become essential to find new solutions to satisfy high gain and larges or multiple bandwidths covering different frequency ranges for these technologies.

Microstrip patch antenna is one of the most satisfactory elements for the future technology due to its advantages such as low weight, low profile planar configuration, low fabrication costs and capability to integrate with microwave integrated circuits technology, it consists of a thin metallic conductor supposed on a dielectric substrate, and supported by a ground plane.

Also, Metamaterial antennas are promising to be a good candidate to enhance performances of a system, it increases the radiated power of the antenna. They are materials which can attain negative magnetic permeability provide many properties such as an electrically small antenna size, high directivity, and tunable operational frequency. Furthermore, metamaterials-based antennas can demonstrate efficiency bandwidth performance.

Many designs have been studied and reported to reduce the size and improve the characteristics of the antenna. In this work, a new multiband design of Microstrip patch antenna is proposed from a simple rectangular patch antenna with a low gain and ultra-wide band.

The chosen antenna consists of a rectangular patch etched on $FR4-substrate$ with $50\ \Omega$ feed line. The rectangular patch has one round cut at each corner with one slot in the ground plane. The rejected bands are the $WLAN$ and $X-bands$, achieved by inserting $H-slot$ in the patch. Then a metamaterial antenna design with the same parameters is studied and compared with the first metallic one, This can be the first step to smart antennas which can present self-parameters control such as auto impedance matching, auto beam forming and auto frequency tuning .The high frequency structure simulator (HFSS) is used to design and simulate the antenna behavior over the different frequency ranges.

This dissertation is divided in three chapters ,the first one present a description of metamaterials, the second chapter contains a presentation of Microstrip patch antennas, their feeding techniques, their advantages and disadvantages and characteristics, it presents also the characteristics of the ultra-wide and multi-band antennas, their applications, advantages and disadvantages and the slot's effect in microstrip patch antenna .The last chapter presents the detail of simulation which is carried out using the simulation software HFSS (high-frequency structure simulator).

CHAPTER 1 :
STATE OF THE ART

1. State of the art

1.1.Introduction

Metamaterials are materials that have electromagnetic properties not found in natural materials. Metamaterials artificial, often periodic structures of very short period compared to the wavelength. The term "meta" comes from Greek and is translated by "beyond" in English, as metaphysical or metalogical. So, metamaterials are materials with properties "beyond" what we can hope to observe in natural materials more precisely, in electromagnetism and optics, metamaterials present new properties likely to excite the imagination of researchers and engineers (the negative refractive index, the doppler effect reverse ....). The most important point for metamaterials is that the negative refractive index (N <0).

Metamaterials are used to improve the performance of antennas, filters and couplers. Their main advantage is the miniaturization of the devices thanks to a fairly easily adjustable refractive index which can even be negative at certain frequencies [1].

2.2. The history of metamaterials

The history of metamaterials began in 1967 when the physicist V. Veselago wondered, from a conceptual point of view, what properties would have a material whose permittivity and permeability would be negative in the same frequency range. After the theoretical study certain properties were predicted by V. Veselago in his article of 1967, such as the inversion of many classical properties like Snell-Descarte's law and the doppler effect [2].

Unfortunately this study is confronted with a physical reality that is to say such a material does not exist in nature, which will make the experimental demonstration of its predictable properties impossible, because of that the article by V. Veselago received little attention when it was published, the subject remained a dead letter for many years.

For the subject to really start it was necessary to wait until the end of the 1990s, with J. Pendry and his collaborators who produced two network structures: thin metal wires (Metal thin-wire) and the split ring resonator (SRR: split -ring resonators) [3]. These two types of structures make it possible to obtain respectively negative permittivity and permeability under certain conditions. In 2000 Smith and his collaborators combined the two Pendry structures in a composite structure to produce the first prototype of material with permeability and negative permittivity simultaneously.

The experimental verification of the negative refractive index was done by D. Smith, Shelby and Schultz at the University of California in 2001 [2].

The property of negative refractive index was already remarkable, but could have remained a laboratory curiosity. But what really drew attention to these exotic materials was the proposal by J. Pendry of the possibility of making a super lent whose resolution would no longer be limited by the classical laws of optics. Finally, in 2006 to crown this subject J. Pendry and U. Leonhardt proposed the realization of an invisibility cloak using Metamaterials.

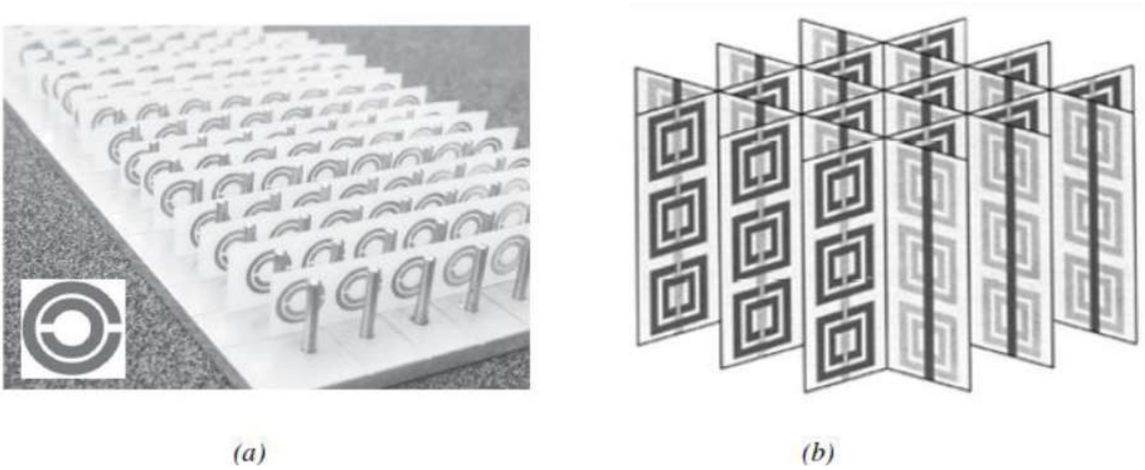


Figure 1.1. *First metamaterial structure, made up of fine wires[2]*

1.3. Definition of metamaterials

Electromagnetic metamaterials (MTMs) are defined as effectively homogeneous electromagnetic structures with unusual properties that are not available in nature (such as having a negative permittivity and permeability, and a negative refractive index). An efficiently homogeneous structure is a structure whose mean structural cell size p is much smaller than the guided wavelength λg. Therefore, this average cell size should be at least less than a quarter of the wavelength: $p < \frac{\lambda g}{4}$ [2].

The constitutive parameters are the permittivity ε and the permeability μ which are related to the refractive index by the following relation:

$$\eta = \pm \sqrt{\mathcal{E}rUr} \quad (1.1)$$

With the refractive index we can order the materials according to a new classification, it is based on the different values of the permittivity ε and the permeability μ. There are four possible combinations of torque (ε, μ): (+, +), (+, -), (-, +), (-, -).

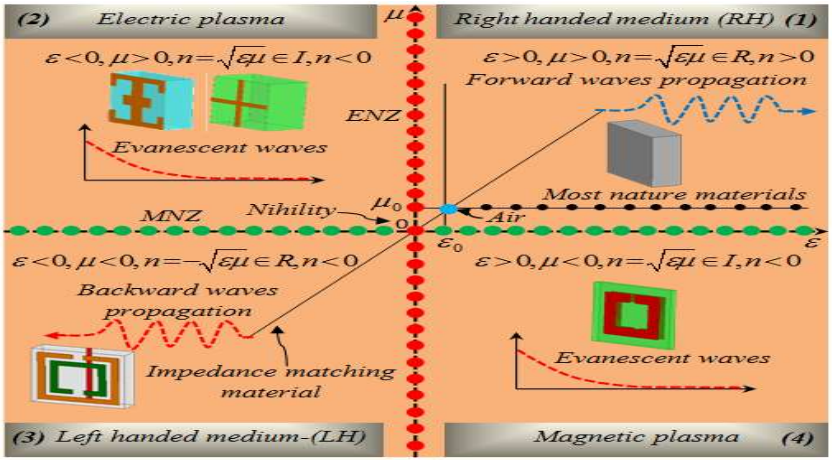


Figure 1.2. *Classification of materials according to the sign of their permittivity and permeability.*

The first three are not new. In fact, the zone (+, +) where the media are double positive (DPS) corresponds to conventional materials known as right-hand materials, such as for example dielectrics. Media with a permittivity [ENG, (-, +)] or a permeability [MNG, (+, -)] negative have also been known for a long time in electromagnetism. The Drude-Lorentz model which applies to most materials predicts regions below the plasma frequency where the permittivity is negative. The three classes of materials (DPS, ENG and MMG) can be found in nature, however double negative media [DNG, (-, -)] do not exist in nature but physically, they are achievable.

1.4. Metamaterial characteristics

The structural units of metamaterials can be tailored in shape, size, and the composition. The inclusions composition and morphology can be designed and artificially tuned, and placed in a predetermined manner to achieve prescribed functionalities.

The dependence of metamaterial properties on the unit cell architecture provides great flexibility to control metamaterials electromagnetic responses which are described by the electric permittivity and the magnetic permeability. So, by varying the different unit cell geometry parameters, we can create an agile metamaterial which electromagnetic response is unavailable in nature and can be tailored in practice to a reach desired profile. Metamaterial tailoring is one of the important advantages of metamaterials.

1.5. Metamaterial classes

Permittivity ε and permeability μ are two parameters used to characterize the electric and magnetic properties of materials interacting with electromagnetic fields.

I.5.1. Metamaterials with negative permittivity

The structure with negative permittivity ($\varepsilon < 0$) described by Pendry consists of infinitely thin parallel metallic wires (**figure 1.3).**

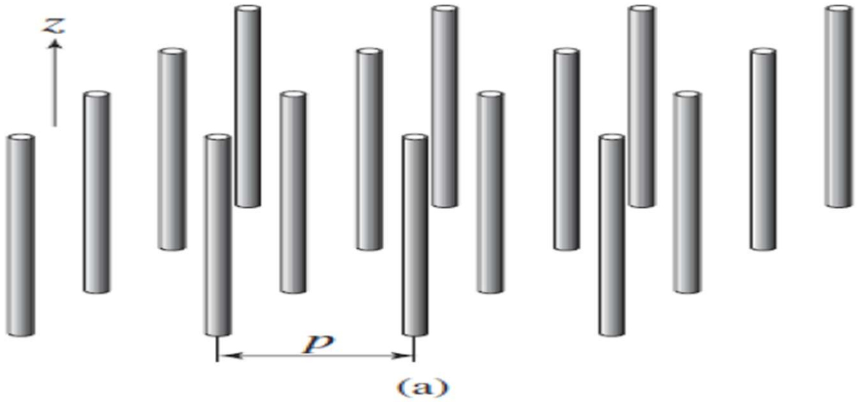


Figure 1.3. *Structure fine wires presenting negative, μ positive when E ∥ z.*

This structure has an average cell size much smaller than the guided wavelength λ_g ($p \ll \lambda_g$), it is an effectively homogeneous structure.

If the electric field excitement $\vec{E}$ is parallel to the axis of the wires, there will be an induced current along these wires, in addition to the equivalent dipole moments are generated.

The permittivity of metallic wires subjected to the electric field $\vec{E}$ is given by the following expression:

$$\varepsilon(\omega) = 1 - \frac{\omega^2_{pe}}{\omega^2} \qquad (1.2)$$

With :

ω_{pe}: Frequency of electrical plasma of metallic wires.

ω: Source excitation frequency.

I.5.2. Metamaterials with negative permeability

The structure with negative permeability (μ <0) described by Pendry consists of an arrangement of split ring resonators (Split Ring Resonator''SRR''). (**Figure 1.4**).

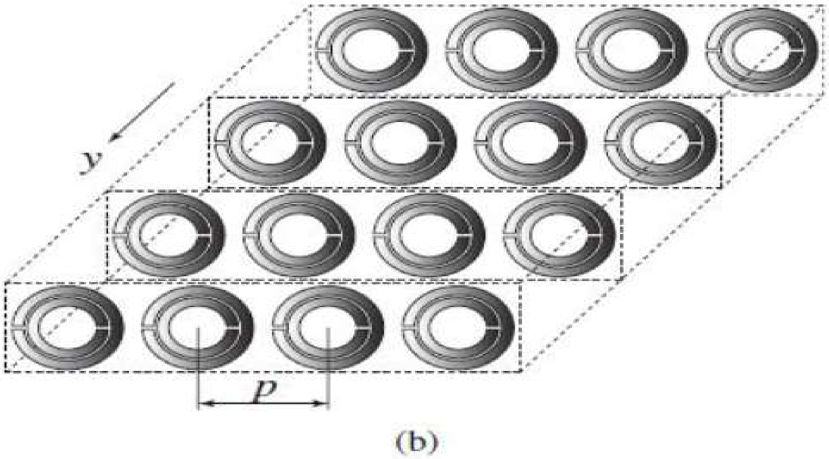


Figure 1.4. *Split ring resonator structure with ε positive and μ negative when* $H \perp z$ [2]

This structure has an average cell size much smaller than the guided wavelength λg ($p \ll \lambda g$), it is an effectively homogeneous structure.

1.6. Artificial Dielectrics

Artificial dielectrics, the first known metamaterials, usually consist of artificially created molecules: dielectric or metallic inclusions of a certain shape. These molecules can be distributed and oriented in space, either in a regular lattice or in a random manner.

The dimensions of the molecules and characteristic distances between neighboring ones are assumed to be very small, as compared to the wavelength. In artificial materials, the size of a single inclusion is usually much larger than those of real molecules and lattice periods of natural crystals. The electromagnetic waves see the inclusions as homogeneous medium. Then, we can describe it in terms of effective material parameters as well as apply the classic Maxwell's equations on these artificial dielectrics formed macroscopically.

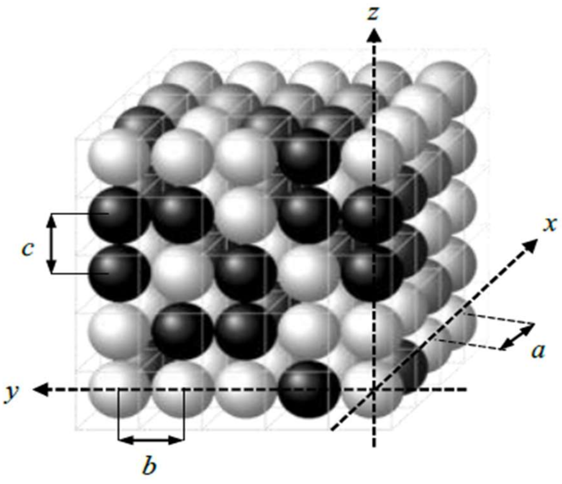


Figure 1.5. *The geometry of a generic artificial dielectric.*

The concept of artificial dielectrics was perhaps first introduced in [4], who used it to design low weight dielectric lenses at microwave frequencies. Metallic inclusions of various shapes with sizes that are small compared to the wavelength are used to artificially produce a high permittivity material. A very interesting example of artificial dielectrics is the wire medium, which has been known since 1950s. It is formed by a regular lattice of conducting wires.

1.7. The microscopic view of metal thin wire

Based on the effective medium theory, metamaterials can be characterized by effective electric permittivity and magnetic permeability. Pendry realized the artificial electric plasma using a metallic wire medium whose permittivity is negative [5] and the artificial magnetic plasma whose permeability is negative [6]. Metamaterials open a door to realize all possible material properties (desired electromagnetic properties tailoring) by designing different unit cells and using different substrate materials [7]. The various, usual and unusual material parameters provided by metamaterials *(*$\varepsilon_{eff} > 0,\ \mu_{eff} > 0,\ \varepsilon_{eff} < 0,\ \mu_{eff} < 0,\ \varepsilon_{eff} \approx 0$, μ_{eff} *and* $n \approx 0$ *...)*, lead to many interesting phenomena and applications.

The metal thin wire unit cell, presented in Figure 1.6 (b), exhibits a plasmonic type permittivity frequency function of the form:

$$\varepsilon_{reff}(\omega) = 1 - \frac{\omega_{pe}^2}{\omega^2 - j\Gamma_e\omega} \tag{1.3}$$

In real and imaginary parts, plotted in figure 1-4 (c), equation (1-19) becomes:

$$\varepsilon_{reff}(\omega) = 1 - \frac{\omega_{pe}^2}{\omega^2 + \Gamma_e^2} + j\frac{\Gamma_e \omega_{pe}^2}{\omega(\omega^2 + \Gamma_e)} \tag{1.4}$$

Where ω_{pe} and Γ_e are the electric plasma frequency and the damping factor due to metal losses respectively.

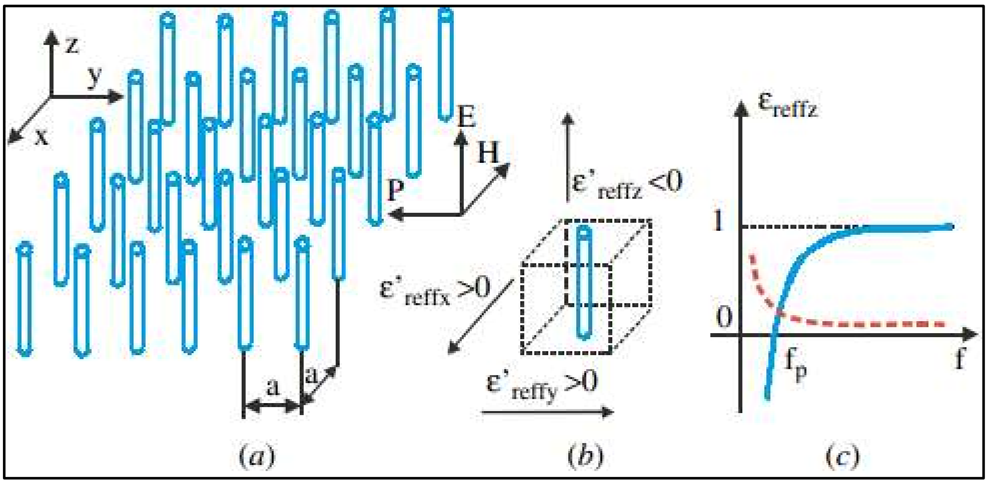


***Figure 1.6**. Real and imaginary parts of effective permittivity of metamaterial [8]*

The Drude parameters ω_{pe} and Γ_e are expressed in function of the geometric dimensions (the period ***a*** and the radius of the wire r), the analytic procedure is detailed in [9].

$$\omega_{pe} = \sqrt{\frac{2\pi c^2}{a^2 ln\left(\frac{a}{r}\right)}} \tag{1.5}$$

$$\Gamma_e = \varepsilon_0 \left(\frac{a\omega_{pe}}{\pi\sigma r^2}\right) \tag{1.6}$$

where c is the speed of light and σ is the conductivity of metals.

We observe from equation (1.4) that $Re(\varepsilon_{reff}) < 0$ for $\omega < \sqrt{\omega_{pe}^2 - \Gamma_e^2}$. It means that if there are no collisions, the free electrons movements are in phase of 180° with respect to the applied electric field. In this frequency band, the propagation is not possible and the wave is evanescent and it’s completely reflected on the medium surface.

1.8. Artificial magnetic materials

Artificial magnetic materials are typically synthesized by using resonant elements, such as split ring resonators or Swiss rolls (as shown in figure 1.7). The split ring resonators are more widely used than the Swiss rolls since they can be manufactured using printed circuit technology. Artificial magnetic materials were known as far back as the early 1950s, and a book by Schelkunoff and Friis [10] provides expressions that can be used to calculate the magnetic flux of a split metallic wire loaded with a small capacitor, formed by a pair of parallel metallic plates. Schneider in [11] used a split metallic tube to produce an NMR probe, and in [12], Hardy proposed a Swiss roll resonator to achieve magnetic resonance at [200-2000] MHz. Kostin in [13] has synthesized an artificial magnetic material with frequency dependent positive permeability using a double circular ring resonators.

An artificial magnetic material, which is formed by split ring resonators, possesses negative permeability within a frequency band (bandwidth is typically narrow) near the resonant frequency of the single split ring resonator and it is widely used to create LHMs.

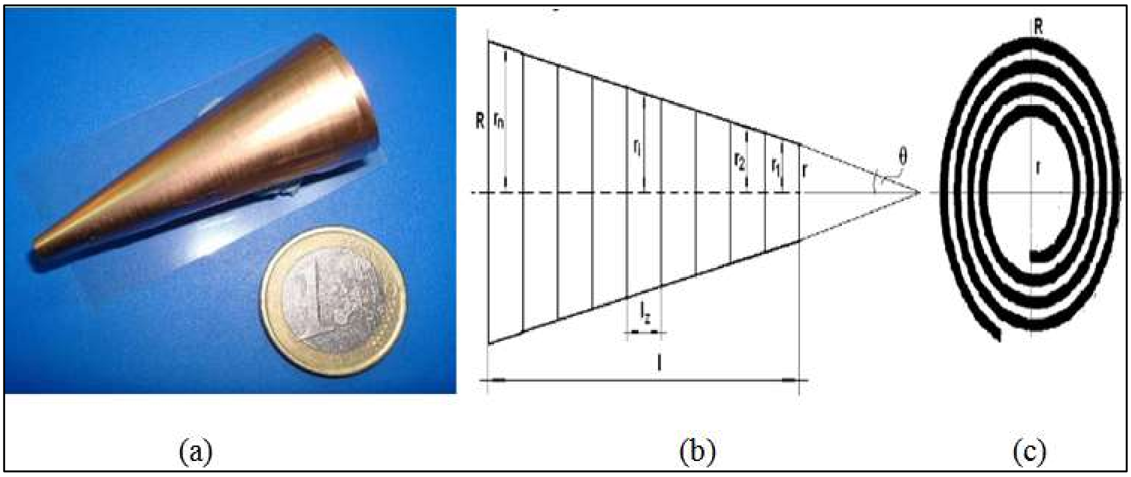


Figure 1.7*. a) Conical Swiss roll unit cell, b) Transversal view, and c) Cross section* [10]

1.9. Overview of metamaterial applications

Due to the exciting and unusual features, metamaterials have found and are finding a lot of applications. Metamaterials can impact on communications, sensing and susceptibility across all wave types, but especially electromagnetics (radio waves to light) and acoustics [14- 15], as it can be seen in Figure 1.8.

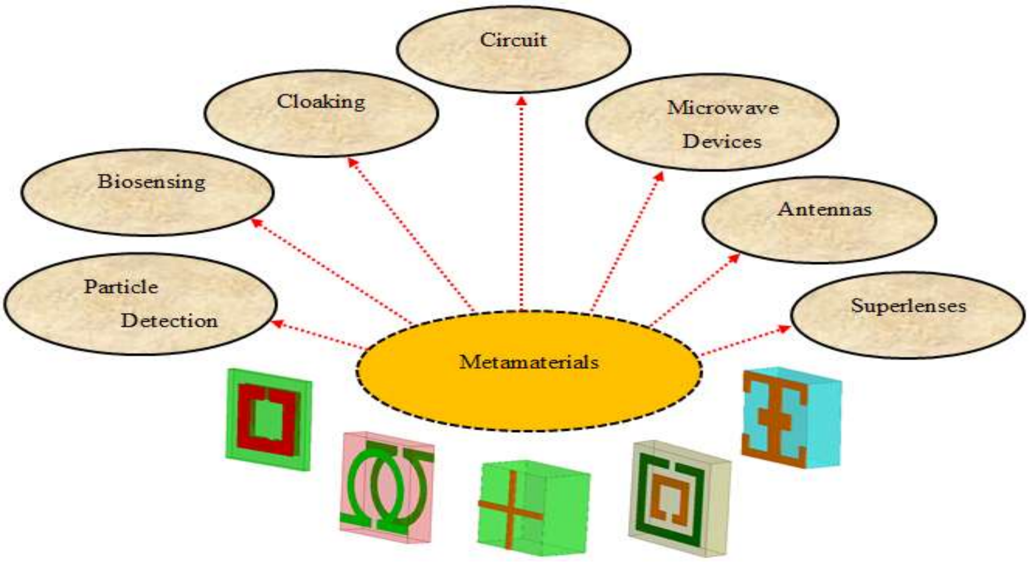


Figure 1.8. *Some proposed metamaterials applications.*

1.9.1. Super lenses

For LHM, the most attractive feature is the super lens, which can be widely used in super resolution medical imaging, optical imaging, and nondestructive detections [16]. A super lens or perfect lens is a lens which uses metamaterials to go beyond the diffraction limit [17]. The diffraction limit is an inherent limitation in conventional optical devices or lenses.

In 2000, a type of lens was proposed, consisting of a metamaterial that compensates for wave decay and reconstructs images in the near field and most importantly the both propagating and evanescent waves contribute to the resolution of the image (Figure 1.9). In 2004, the first super-lens with a negative refractive index provided resolution three times better than the diffraction limits and was demonstrated at microwave frequencies. In 2005, the first near field super lens which exceeded the diffraction limit was demonstrated [18]. The higher focusing resolution will be provided by flat LHM lens if compared to convex dielectric lens and elliptical reflector focusing system. The LHM lens has the potential to acquire higher imaging resolution and easy in depth scanning, which will simplify the detection system design.

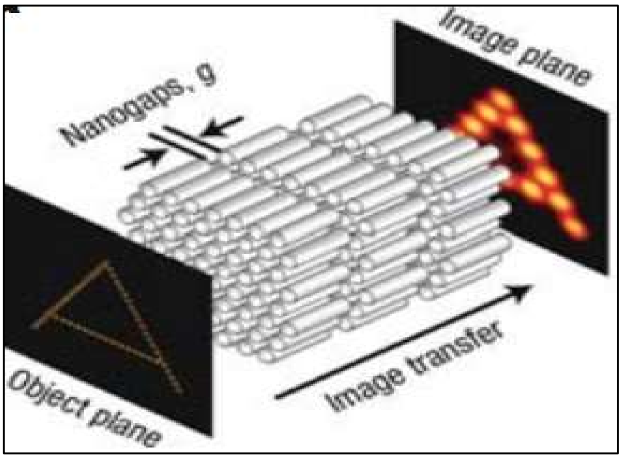


Figure 1.9. *Super resolution imaging using a metamaterials nano lens.*

For example, in biological domain, microwaves are used to destroy or ablate diseased soft tissue by heating the tissue to a temperature that causes cell death. This is called hyperthermia. The generator produces microwave energy which is transmitted through the antennas into the patient. Elevating the temperature of tumor cells causes cell membrane damage, which leads to the destruction of the cancer cells. Hyperthermia treatment of cancer requires directing a carefully controlled dose of heat to the cancerous tumor and surrounding body tissue. The most prominent property of metamaterial lens is the ability of negative refractive index (NRI) to focus the electromagnetic field of a source. Hence it can generate appropriate focusing spot in biological tissue as required in microwave hyperthermia treatment. Flat metamaterial slab has been used as a lens to focus microwave energy emitted from the microwave source. In this application, a planar array of split-ring resonators placed between two parallel metallic plates and is fed by a small loop antenna to excite the split-rings. Recently, conformal microwave array applicators with proper source spacing and low loss LHM lens were used for hyperthermia treatment [18].

1.9.2. Antennas

Metamaterial antennas can enhance or increase performances of a system. It increases the radiated power of an antenna. Materials which can attain negative magnetic permeability provide many properties such as an electrically small antenna size, high directivity, and tunable operational frequency. Furthermore, metamaterials based antennas can demonstrate efficiency bandwidth performance.

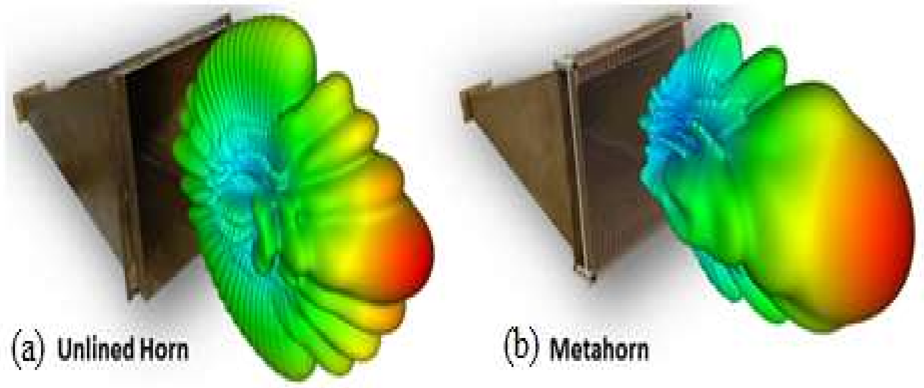


Figure 1.10. *The rectangular horn antenna: a) alone, and b) with metamaterial.*

Metamaterials employed in the ground planes surrounding the antennas offer improved isolation between radio frequency or microwave channels of Multiple-Input Multiple-Output (MIMO) antenna arrays. Metamaterial, high impedance ground planes can also be used to improve the radiation efficiency (Figure 1.10), and axial radio performance of low profile antennas located close to the ground plane surface. They have also been used to increase the beam scanning range using both the forward and backward waves in leaky wave antennas. Various metamaterial antenna systems can be employed to support surveillance sensors, communication links, navigation systems, command and control systems [17].

The gradient refractive index metamaterials are also utilized to produce beam bending and beam focusing lenses. Based on such properties, high gain, and broadband gradient, planar lens and Luneberg like lens antennas have been proposed and realized [19]. The Industrial, Scientific and Medical (ISM) radio bands are portions of the radio spectrum reserved internationally for the use of radio frequency (RF) energy for industrial, scientific and medical purposes other than communications. By using EBG (Electromagnetic Band Gap) structures in slotted microstrip antenna, increased efficiency and better return loss characteristics can be achieved. A patch antenna with slotted ground plane has been developed in which EBG structure is used as a metamaterial above the ground plane [18].

1.9.3. Microwave devices

Planar metamaterials which are composed of complimentary structures have been used to design microwave components like filters, power dividers, and phase shifters [8]. Narrowband and broadband polarizers have been realized using three dimensional (3D) anisotropic metamaterials [16] (Figure 1.11).

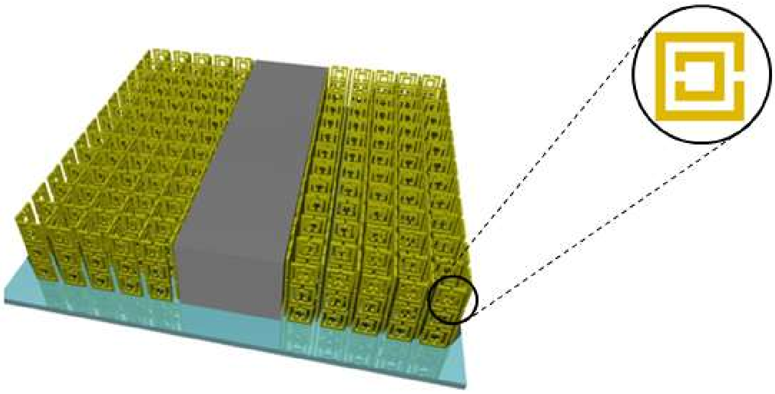


Figure 1.11. A planar waveguide with double SRR metamaterial.

Superconducting metamaterials have been achieved in addition to superconducting split rings and wires. They have been utilized to realize a number of unique applications [19]. The combination of left and right handed propagation media creates new type of resonant structures by laminating two materials with opposite senses of phase [8]. This material is used to design an ultra-compact resonator whose overall dimensions are unconstrained by the wavelength of the resonant wave. The proposed resonator consists of two flat conducting plates separated by a sandwich of left-handed and right-handed metamaterials. A wave propagating in the direction normal to the plates will suffer a combination of forward and reverse phase windings before reaching the other reflecting boundary. Under these conditions, the wave could undergo a net phase shift of zero radians and still create a resonance condition.

The net phase shift could also be a positive or negative multiple of 2π radians [19] as well, each creating a resonant condition.

Superconductors are particularly attractive for use in ultra-compact resonators and showed resonances with indices between +2 and -6, including zero, over the broad frequency range from about 5 to 24 GHz [19]. Quality factors of the negative order resonances were on the order of 3000 at 30 K, while those for positive order resonances were below 400.

1.9.4. Cloaking

Cloaking devices still attract more and more attention, particularly in the military field. The successful demonstrations of invisible cloaks experimentally in the microwave regime open the possibility to realize cloaking devices [16]. Metamaterials are a basis for attempting to build practical cloaking devices. The cloak deflects microwave rays, so they circumvent the object inside with little distortion (Figure 1.12), making it appears almost as if nothing were there at all. Such a device typically involves surrounding the object to be cloaked with a shell which affects the passage of light near it [17].

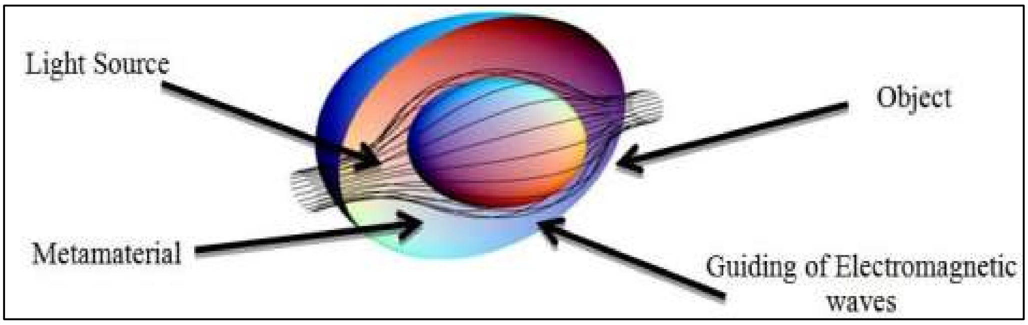


Figure 1.12. *Invisibility cloaks.*

1.9.5. Absorbers

Specific absorption rate is a measure of how much radiation is absorbed by human body. The basic principle behind the metamaterial absorbers (Figure 1.13) is, when one of the effective medium parameter is negative and the other is positive, the medium will display a stop band. The stop band of metamaterials can be designed at operating bands of cellular phone. The unit cells are designed to operate at certain frequency band. The structure parameters of unit cells are chosen in order to behave as an effective medium with negative refraction index around this frequency band [18]. The metamaterials can be designed on circuit board, so it may be easily integrated to the cellular phones [18].

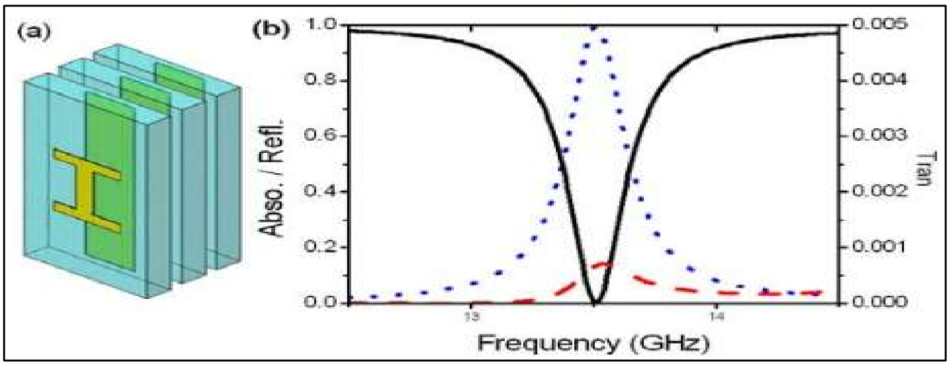


***Figure 1.13**. Three layer model of the simplified absorber structure*

1.9.6. Acoustic metamaterials

Acoustic metamaterials are designed to control, direct, and manipulate sound in the form of sonic, infrasonic, or ultrasonic waves (Figure 1.14), as these might occur in gases, liquids, and solids [17]. They can be used to cloak objects or vehicles from radar, sonar, or other sound detection systems [21].

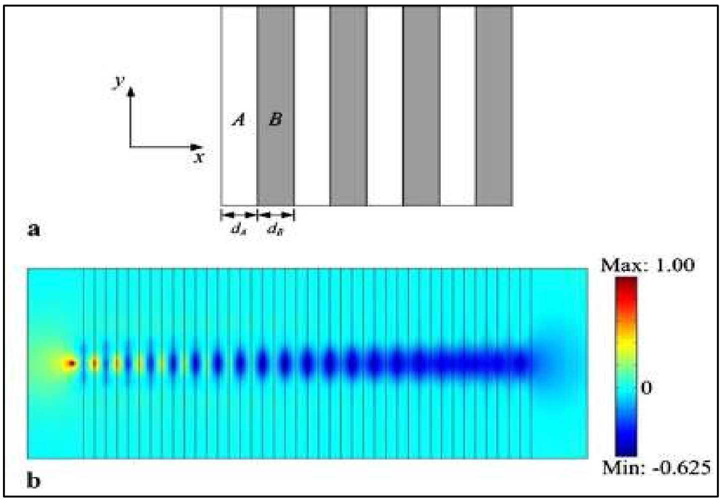


Figure 1.14. *Alternating layered structure to implement the anisotropic material [22].*

1.10. Microwaves filters

In microwave wireless systems, different microwave filters are used such as stopband filters (SBFs) and bandpass filters (BPFs) in different applications. The miniaturization and the device performance are the key issues when metamaterials (MTMs) are used to design microwave devices such as antenna, filter and diplexer. The first theoretical assumption on the existence of double negative media and prediction of its fundamental properties was mentioned by Russian physicist V. Veselago in 1967. There are several equivalent terms which have been used as MTMs with negative permittivity and permeability, such as; left-handed (LH) media, media with negative refractive index (NRI), backward wave media (BW), double-negative (DNG) metamaterials, Veselago medium, or negative phase velocity medium (NPV). Left-handed metamaterial (LHM) presents new structures in modern microwave science; by which the design of novel microwave components such as filters with advantageous characteristics and small dimensions are achieved. Many research groups are studying various aspects of metamaterials, and several ideas, concepts and suggestions for future applications of these materials.[23].

The realization of backward wave propagation using SRR and thin wire (TW) to get negative permeability and negative permittivity, respectively, and several other electrically small resonators was presented by Pendry et al [24], [25] .

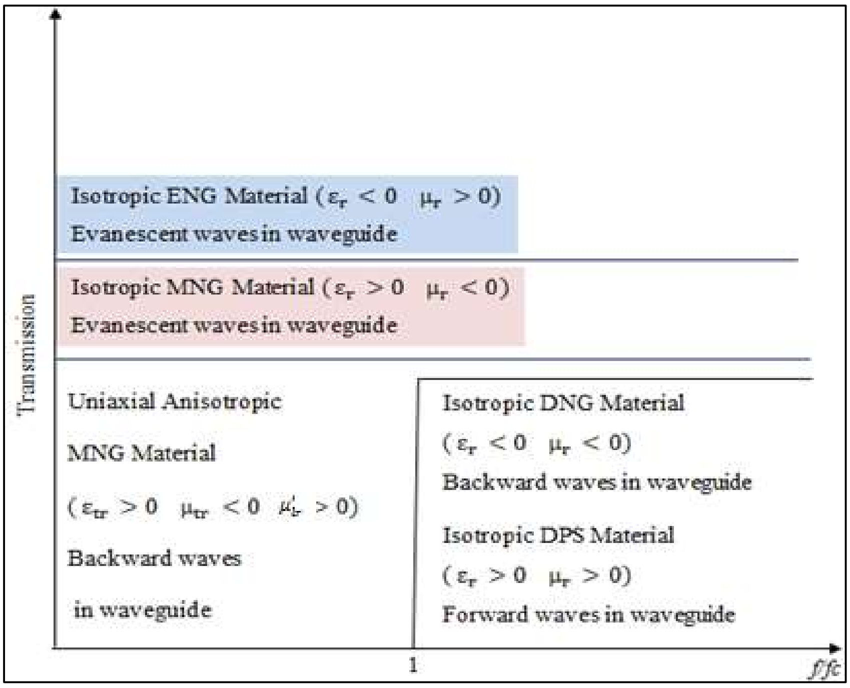


Figure 1.15. *A metamaterial waveguide transmission bands for different material parameters sign.*

1.11. Frequency Selective Surface (FSS)

The frequency selective surfaces (FSS) (figure 1.16) are periodic structures in either one or two dimensions (singly or doubly periodic structures). Figure 1.17 illustrates some inclusion shapes used in FSS designing.

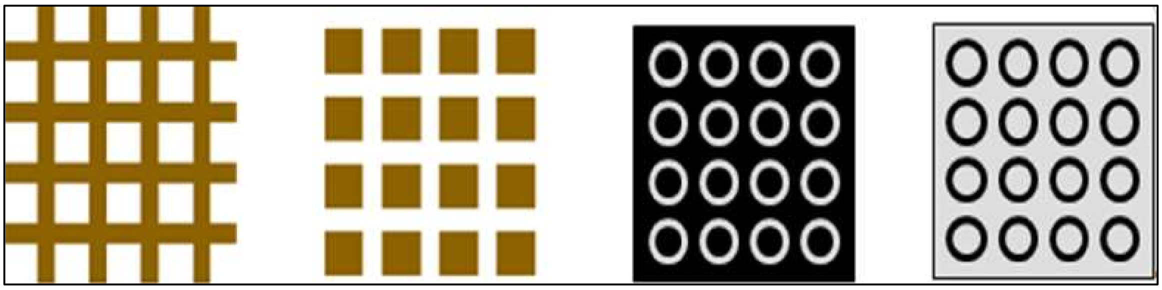


***Figure 1.16**. Different FSS structures [26-27].*

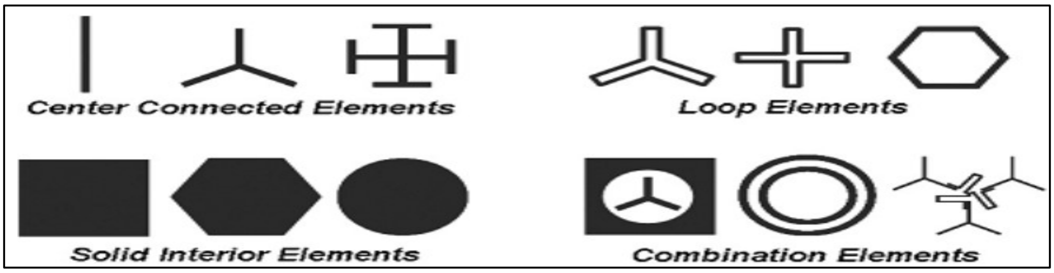


***Figure 1.17**. Different FSS inclusion shapes.*

At microwave and optical frequency ranges, spatial filtering is the most desirable operation in all signal processing systems. Frequency selective surfaces (FSS), also called spatial filters, are used to modify the EM wave incident on such surfaces and provide dispersive transmitted and/or reflected characteristics. FSSs are usually designed by periodic metallic arrays of elements on a dielectric substrate. The change brought to the transmitted wave can be both in amplitude or phase when compared to the incident wave. In any case, selectivity may be introduced against the incident polarization to improve the irregularities in the emission pattern, which is exhibited through a change of the phase or amplitude of the transmitted wave. A variety of applications according to different requirements can be facilitated, depending on the nature of modification added to the transmitted wave [28].

The patch elements (dipole FSSs) are designed to act as stopband filters for incoming plane waves and work as completely reflecting surfaces in a narrow band of frequencies. Their counterparts, the aperture elements (slot FSSs), demonstrate passband characteristics, means that they behave as transparent surfaces to incident EM waves within the working band of frequencies. Nevertheless, to accomplish the functional necessities for a variety of EM applications, conventional FSSs come across a limited use due to their inadequate filter response, low angular stability, and narrow bandwidth.

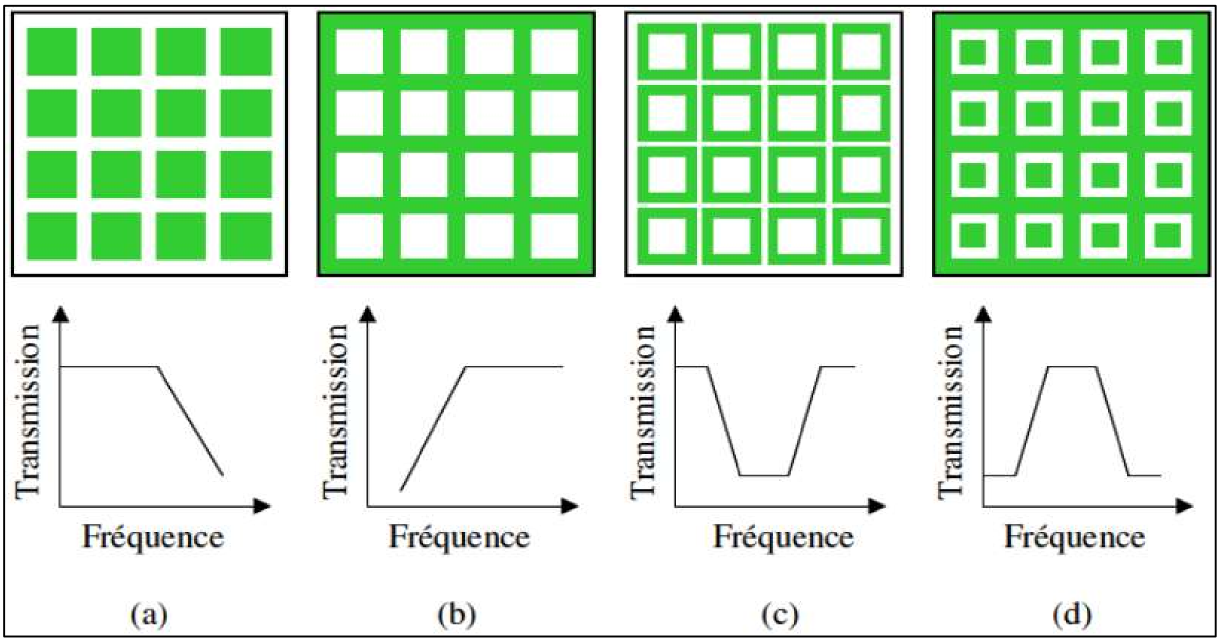


Figure 1.18. *Filter types based on FSS [29].*

1.12. Conclusion

In this chapter, we have focused on definitions, origin, fundamental properties of metamaterials. These artificial materials were predicted by Veselago as a left hand. But it is only recently that this thematic has known a great progression, following the presentation made by J. Pendry in which he announced the possibility of creating artificial structures presenting a permeability and / or a negative effective permittivity. This was affirmed by the experimental demonstration of D. Smith. The most used means to create an artificial permeability are the SRRs (Split Ring Resonator). These are split metal loops creating an LC resonance comparable to ferromagnetic resonance. For negative permittivity, the principle consists in using a network of metal rods. The combination of the two structures leads to metamaterials with simultaneously negative permittivity and permeability.

CHAPTER 2:

Overview about antennas and their characteristic parameters

I. Microstrip antennas

I.1. Introduction

The telecommunications sector becomes an integral part of our lives. In recent years, it has experienced technological progress thanks to the high demand from the population and from industry. Among the applications in this area which have attracted more attention and are present in all wireless communication systems are the antennas. They are essential elements for ensuring an operation of emission or reception of electromagnetic waves in the Earth's atmosphere or in space.

Because of their many uses, today, planar antennas are of great interest to researchers. Indeed, the preferred areas of use of microstrip antennas are high frequency communications such as space communications, military and commercial satellite positioning systems (GPS), air or land navigation, wireless computer networks (Wireless Local Area Network), communication between two mobiles and in new fields such as medicine or mobile phones. This wide and important use of these antennas is mainly due to the various advantages that they can offer compared to conventional antennas such as: low weight, volume and thickness, very low manufacturing cost, easy mass production, possibility of setting up network and integration of discrete elements and conformability facilitating installation on any type of support.

With the rapid growth of the wireless mobile communication technology, the need of the wide band and multi band antenna is increased to serve various wireless technologies using different frequencies, and it has become essential to find new solutions to satisfy high gain and larges or multiple bandwidths covering different frequency ranges for these technologies , one of these solutions is to use antenna with slots . By the way the future technologies need a very small antenna and also the need of wide band and multi band antenna is increased to avoid using two antennas.

I.2. Description of a microstrip antenna

A microstrip antenna, as shown in Figure 2.1, consists of a thin metallic conductor of arbitrary shape, called a radiating element, deposited on a dielectric substrate whose underside is fully metallized to produce a ground plane [30].

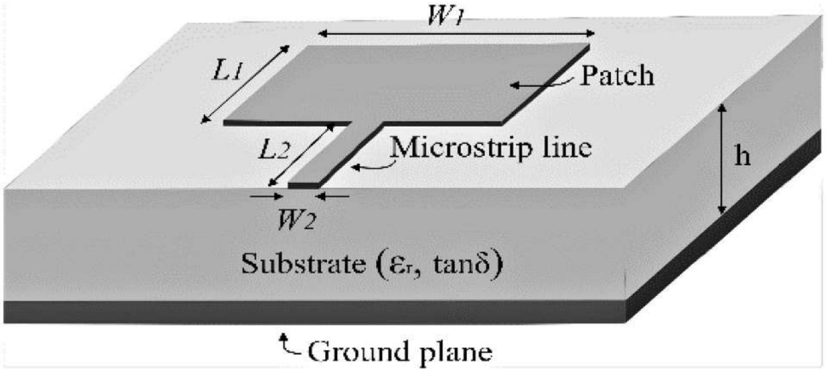


Figure 2.1. *Typical structure of a microstrip antenna*

I.2.1. The different shapes of a microstrip antenna

The patch antenna can take many forms which can be rectangular, square, circular or simply a dipole. These forms are the most common because they present great ease of analysis and manufacturing. Generally, the characteristics of the antenna depend on the shape and dimensions of the patch; thickness and dielectric constant of the substrate and the excitation technique [31]. Figure 2.2 shows these different forms [34].

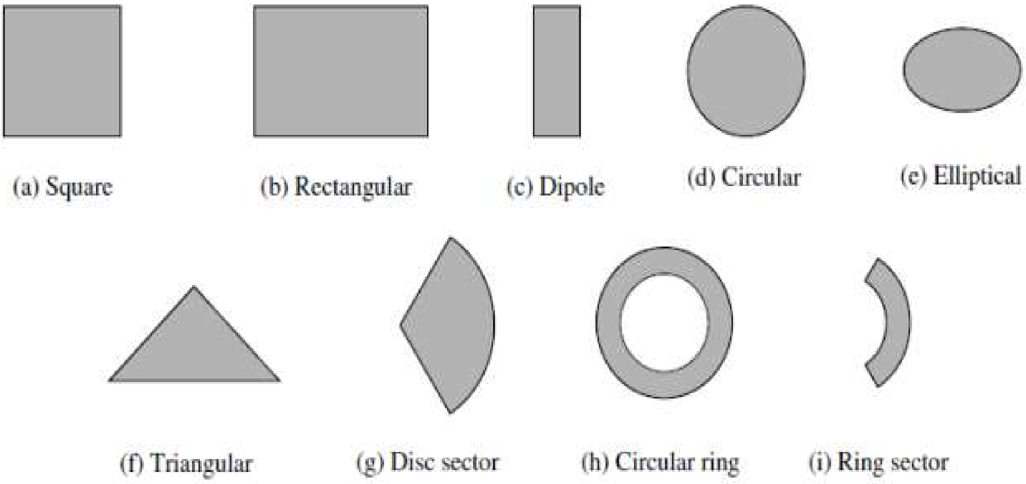


Figure 2.2. *Different forms of patch antennas.*

I.2.2. Substrates

There are a multitude of dielectric materials for substrates. The important parameters are: the dielectric ($2 < \varepsilon r < 16$) in the RF or microwave band). The class of values of the dielectric constant of the substrate ranges from 2.2 to 12 to operate at frequencies ranging from 1 to 100GHz [35]. The losses in the dielectric are represented by a tangent ($0.0001 < \delta < 0.06$) or the imaginary part of the dielectric constant [31] [36]. Because of their low cost, their ease of manufacture and their good adhesion surfaces, plastics are commonly used in the RF band. Another consideration to take into account when choosing the substrate is the effect of the dielectric constant on the radiation characteristics. A large dielectric constant generally results in weak radiation from the patches [31].

I.2.3. The dielectric materials used in substrates

The substrate plays a double role in microstrip technology. It is both a dielectric material, where circuits are etched, and a mechanical part, because it supports the structure. This implies both mechanical and electrical requirements which are sometimes difficult to reconcile, which are generally thin compared to the operating wavelength ($h \ll \lambda_0$). The dielectric substrate affects the behavior and electromagnetic performance of the antenna. It is often preferred to use substrates with low dielectric losses ($\tan\delta < 10^{-3}$) which favor the efficiency of the antenna and those with low relative permittivity ($\varepsilon r < 3$) which improve the radiation while decreasing the losses by surface waves for a given height [31]. The materials used are [37]: Ceramic materials, Semiconductor materials, Ferromagnetic materials, Synthetic materials, etc.

I.3. Techniques for excitation of a microstrip antenna

Excitement is a very important point when studying printed antennas. Indeed, energy is supplied to the radiating element in a way where we can directly influence its radiation and modify its performance. The power of the antenna depends on the way the antenna is integrated in the device. The methods of feeding the microstrip antennas can be classified into two categories:

- Contact power supplies (by probe or micro ribbon line).
- Proximity power supplies (electromagnetic coupling by line or slot) [38].

I.3.1. Direct alimentation (with contact)

In this contact alimentation technique, two types can be distinguished.

I.3.1.1. Power supply by microstrip line

This technique consists in placing a micro-ribbon line (generally 50 Ohms) in contact with the radiating element (Figure 2.3). The length of the line is considered smaller than the dimensions of the patch. This fairly simple principle provides the possibility of fabricating a planar structure on a dielectric substrate.

This advantage is the origin of a wide use of a micro-ribbon supply in the arrays of printed antennas of different shapes [39].

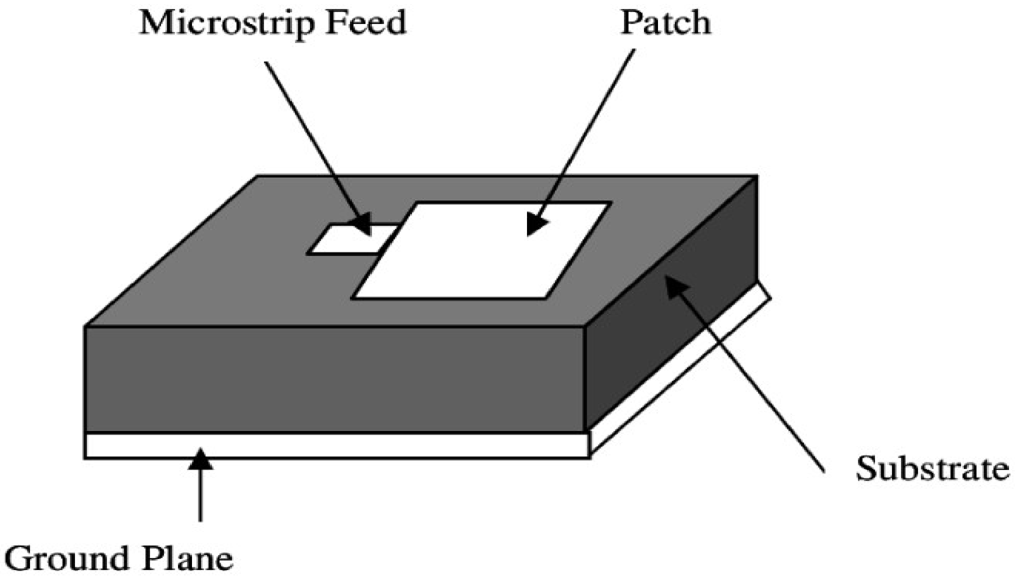


Figure 2.3. *Microstrip line supply*

I.3.1.2. Coaxial cable power

The power supply with coaxial cable or power supply by probe is a technique widely used to power micro ribbon antennas (Figure 2.4). In this case, the inner conductor of the coaxial connector crosses the dielectric and is welded to the patch, while the outer conductor is connected to the ground plane.

The main advantage of this type of feeding is that it can be applied to any chosen location inside the patch, with ease of manufacture. However, this method has drawbacks in terms of the radiation diagram. Indeed, the connection generates a current peak located at the level of the radiating element which can induce an asymmetry in the radiation diagram. In addition, losses appear with the drilling of the ground plane, the dielectric as well as the radiating element [40].

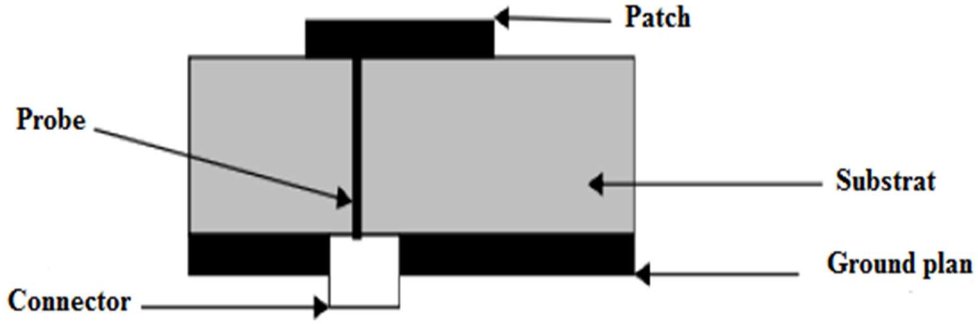


Figure 2.4. *Micro ruban antenna supplied by probe*

I.3.2. Power supply by coupling (contactless)

I.3.2.1. Feeding by opening (slit)

In this type of power supply, the radiation patch and the power supply line of the microstrip are separated in ground plane as shown in Figure 2.5. The connection between the patch and the supply line is made by an opening or a slit in the ground plane. The ground plane isolates the supply line of the radiating element and limits the interference of the parasitic element on the radiation diagram and offers greater purity of polarization [31]. Generally, materials with high permittivity are used for the lower substrate, on the other hand materials with low dielectric constant are used for the upper substrate in order to optimize the radiation of the patch. This type of feed is difficult to conceive because of the multiple layers, which increase the thickness of the antenna. However, it does offer bandwidth expansion [38].

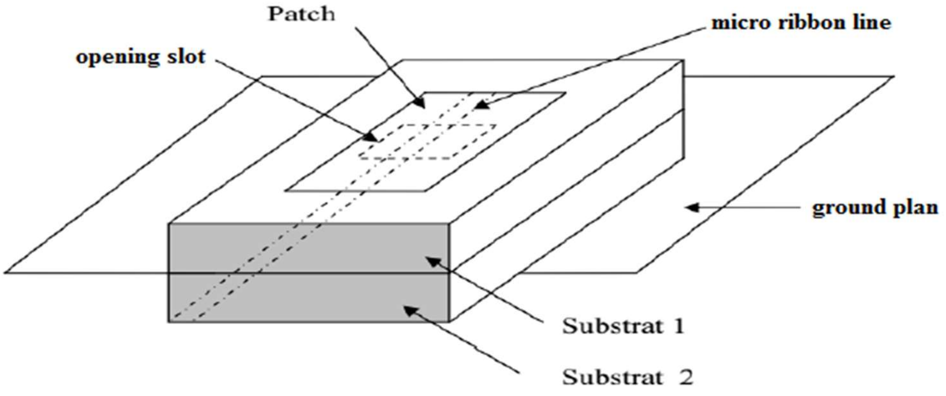


Figure 2.5. *Supply coupled by opening [38].*

I.3.2.2. Alimentation by Proximity

This type of supply is shown in Figure 2.6, two dielectric substrates are used such that the supply line is between the two substrates and the radiation patch is on the upper substrate [38].

The best bandwidth of up to 13% can be achieved by using proximity coupling power illustrated in Figure 1.6. The advantage of this feeding technique lies in the weakening of the stray radiation and the ease of coupling, the latter can be optimized by adjusting the dimensions of the line. However, it is very difficult to implement [22].

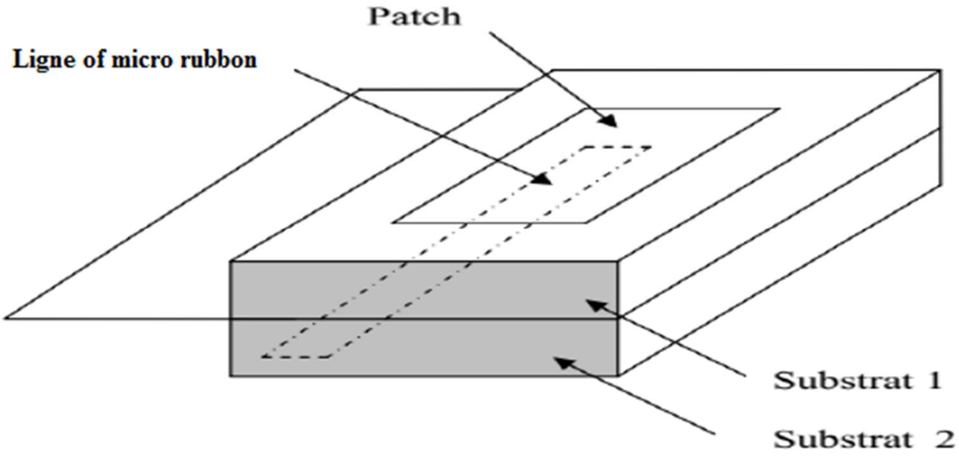


Figure 2.6. *Proximity coupled power supply*

I.4 Operating principle of a microstrip antenna

To understand how a microstrip antenna works, consider the section given in Figure 2.7. At point a of the upper conductor, a point source (surface current density) has been deposited, which radiates in all directions. Part of the transmitted signal is reflected by the ground plane, then by the upper conductor and so on. Some of the rays end up on the edge of the conductor (point b), which diffracts them.

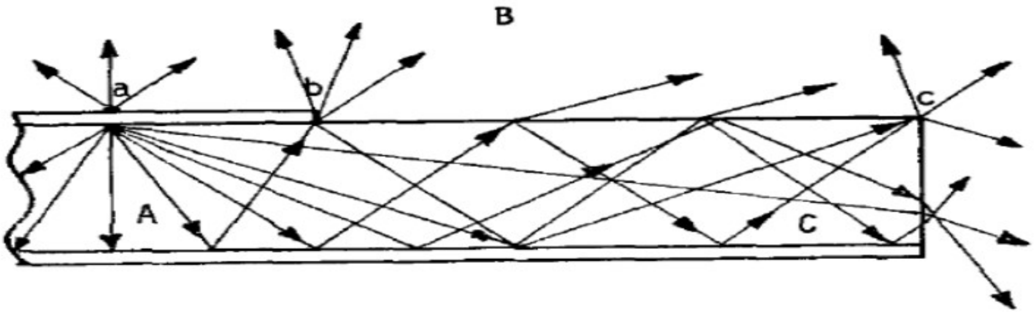


Figure 2.7. *Ray trajectories in a microstrip antenna (section)*

This figure can be divided into three distinct regions:

Region A: In the substrate, between the two conducting planes, the rays are more and more concentrated. The electromagnetic field accumulates in this region of space. This property is very useful for the propagation of the signal along a microstrip line.

Region B: In the air, above the substrate, the signal disperses freely in space and contributes to the radiation of the antenna. As the surface currents flow mainly on the underside of the upper conductor (dielectric side) [31], the radiation seems above all to be emitted by the immediate vicinity of the edges. Some simplified models take advantage of this observation: they consider the radiation of a set of fictitious slots, located around the edge of the antenna.

Region C: Some rays reach the separation surfaces with a grazing incidence and remain trapped inside the dielectric. This is the mechanism of total reflection, which is used by optical fibers. A surface wave is then guided by the edge of the dielectric, not contributing directly to the radiation of the antenna. However, when this wave reaches the edge of the substrate (point c), it is diffracted and generates parasitic radiation. In the case of a network antenna, the surface wave creates a coupling between the elements of the network. The antenna radiation pattern can be disturbed by the presence of surface waves, especially at the side lobes. In principle, surface waves could be used to feed the elements of a network.

Frequency ranges can be associated with the three preceding regions:

Frequency range A: At low frequency, the fields remain mainly concentrated in region A. there is then propagation without radiation. The resulting structure is a transmission line or one of the derived elements.

Frequency range B: At higher frequencies, radiation in the air becomes significant and the structure behaves like an antenna. However, there remains a large concentration of fields between the two conductors (reactive energy stored in the near field area). As the dielectrics always have certain losses, this results in absorption of the signal. The performance of a microstrip antenna therefore remains quite modest.

Frequency range C: Although a surface wave can, in principle, propagate whatever the signal frequency, it is above a certain limit frequency above all that these waves play a significant role. The structure then becomes a surface launcher. It can no longer be used as an antenna, unless you have an adequate transition, which makes the transition from a surface wave to a radiated wave.

I.5. Analysis methods

Several methods are used for the analysis of microstrip antennas. Most of these methods can be classified into one of two categories: approximate methods and rigorous methods (Full-wave) [22] [37].

Approximate methods are based on simplifying assumptions so they have limitations and provide less precise solutions. They are generally used for modeling single element antennas because of the difficulty encountered in modeling the coupling between the different elements. However, they offer a good physical overview with a generally very short computation time. The rigorous methods take into account all the important mechanisms of the wave and rely heavily on the use of efficient numerical algorithms. When applied properly, the rigorous methods are very precise and can be used for modeling a variety of antennas including array antennas. These methods tend to be more complex and provide less physical insight. Often, they require more calculations and therefore a long calculation time [22] [24].

I.5.1. Approximate methods (analytical)

The approximate methods take into account at the outset the nature of the physical phenomena, which makes it possible to make approximations, allowing the modeling of the model in question. Among these methods, we quote:

- The model of the transmission line;
- The model of the cavity.

I.5.1.1 The model of the transmission line

The model of the transmission line is considered to be the simplest. This model exploits the analogy that exists between a patch of a printed antenna and a section of a transmission line having two radiating edges. This model takes into account at the outset the nature of the physical phenomena, which makes it possible to make approximations, allowing the modeling of the model. In the transmission line model, the unknown to determine is the propagation constant. The radiation losses are included in the attenuation coefficient of the propagation constant. However, this technique does not account for the effects of higher order modes [21].

The resonance frequency for the **Tm**$_{0}$ mode can be evaluated at:

$$f_{rm}=\frac{\mathrm{mc}}{\mathrm{mc2}(\mathrm{L}+\Delta\mathrm{L})\sqrt{\varepsilon\mathrm{reff}}} \qquad (2.1)$$

With

$$\Delta\mathrm{L}= 0.412\mathrm{t}\,\frac{(\varepsilon reff+0.3)(\frac{W}{t}+0.264)}{(\varepsilon\mathrm{reff}-0.258)(\frac{w}{t}+0.8)} \qquad (2.2)$$

c: speed of light

m: mode index

L: length of the patch

The dominant mode is T_{10} mode

$\varepsilon_{\mathrm{reff}}$ is the effective dielectric constant. It represents the dielectric constant, homogeneous and fictitious.

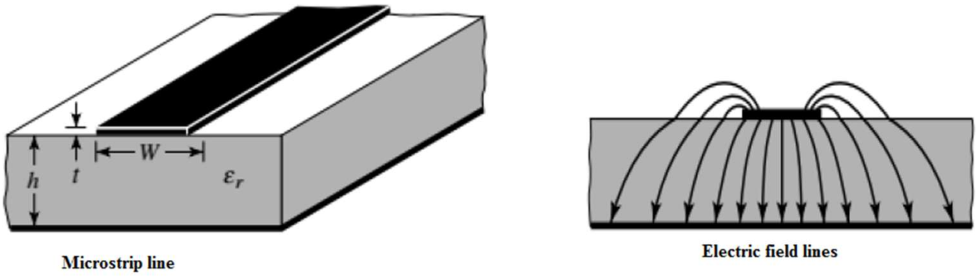
$$\varepsilon_{\mathrm{reff}}=\frac{\varepsilon\mathrm{r}+1}{2}+\frac{\varepsilon\mathrm{r}-1}{2}\,(1+10\,\frac{t}{W})^{-\alpha\beta} \qquad (2.3)$$

In other literatures, equation (2.3) is written:

$$\varepsilon_{\mathrm{reff}}=\frac{\varepsilon\mathrm{r}+1}{2}+\frac{\varepsilon\mathrm{r}-1}{2}\,(1+10\,\frac{t}{W})^{-1/2} \qquad (2.31)$$

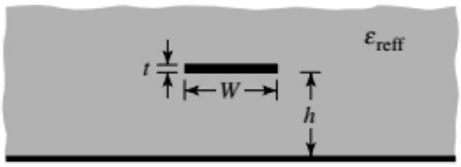
Or

$$\varepsilon_{\mathrm{reff}}=\frac{\varepsilon\mathrm{r}+1}{2}+\frac{\varepsilon\mathrm{r}-1}{2}\,(1+12\,\frac{t}{W})^{-1/2} \qquad (2.32)$$



Microstrip line

Electric field lines



Dummy line with fictitious dielectric constant

Figure 2.8. *Model of the transmission line of a microstrip antenna.*

I.5.1.2 The cavity model

The printed structure can be likened to a cavity closed by two electric walls at the bottom by a ground plane at z = 0, at the top by a conductive plate at z = h, and by vertical magnetic walls. An effective length and width are introduced to take into account the overflows of the fields on the edges of the antenna. For the excitation, we take for model an electric current J parallel to the axis oz and distributed uniformly.

To calculate the internal field in the cavity, the so-called mode connection method is used. It consists in dividing the cavity into two regions I and II devoid of sources and then in solving the Helmholtz equation (without second member) in each region. The far fields are given by the radiation of the vertical openings and the total radiated power is obtained by integrating the far field in all the upper half-space [25].

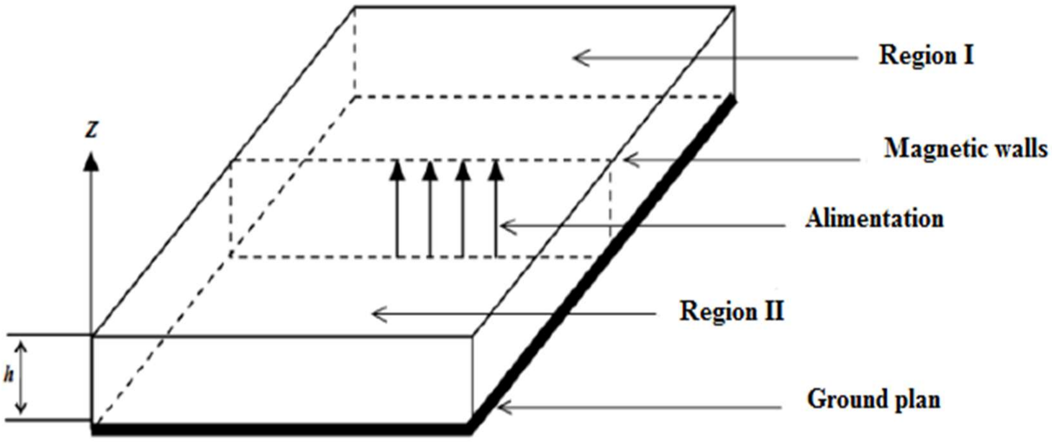


Figure 2.9. Cavity model [45].

I.5.2. Numerical methods

I.5.2.1. Finite element methods

The finite element method based on the resolution of Maxwell's equations and on the geometric description of the structure in the form of a mesh. It consists in dividing the space into small homogeneous elements but of practically very variable size, which constitutes one of the strong points of this method. This method makes it possible to calculate, at each point of the elements dividing the space, the electric fields which minimize the energy function [46]. The finite element method is implemented in some commercial codes such as the famous HFSS software from Ansoft [30].

I.5.2.2. Finite difference methods

It allows the components of the electromagnetic field in each elementary cell of the three-dimensional volume to be calculated at each discrete instant in space. We apply the Fourier transform to the temporal response to obtain the frequency response of the system [26].

The finite difference method has been implemented in commercial software such as Fidelity by Zeland [25].

I.5.2.3. The transmission line matrix method (TLM)

The transmission line matrix method makes it possible to discretize the fields and currents of the structure studied into small elements, each of these elements is considered as a set of transmission lines and the calculations are carried out directly in the time domain. [20].

I.5.2.4. The moments method

The use of the method of moments in electromagnetic problems was developed for the first time by Newman [48], is a way of solving integral equations which makes it possible to reduce these into a system of linear equations applied to planar or quasi-planar structures on 2D structures [21].

I.6. Advantages and disadvantages of microstrip antennas

Microstrip antennas have many advantages compared to conventional microwave antennas and therefore several applications in the wide frequency range from 100MHz to 50GHz are possible. Among these advantages, we can cite [24]:

- Low weight, small volume, planar configuration, low thickness;
- Low manufacturing cost, mass production possible;
- These antennas can be placed on missiles, rockets and satellites without major modifications;
- The antennas have small areas of radiation;
- Linear polarization as in the case of rectangular and circular plate antennas (left or right) is possible with slight changes in the position of the power supply;
- The use of two working frequencies is possible;

- The microstrip antennas are compatible with modular constructions (Monolithic components such as oscillators, variable alternators, switches, modulators, mixers, phase shifters and can be adapted directly on the substrate);

- Power lines and impedance matching circuits are fabricated simultaneously with the antenna structure.

As the microstrip antennas have advantages; they also have some drawbacks compared to conventional microwave antennas such as [29]:

- Narrow bandwidth;

- Lower gain due to losses;

- Practical limitations on gain (maximum 20dB);

- The performance of the longitudinal radiation is poor;

- The insulation between the radiating elements and the supply is poor;

- Possibility of excitation of surface waves;

- Low energy handling capacity.

I.7. Applications of Microstrip antennas

Given the technological explosion in the telecommunications field and the continuous scientific research concerning printed antennas, and given the multiple requirements in the field of communication, the use of conventional microwave antennas becomes incapable of meeting these requirements. For this reason, microstrip antennas replace conventional antennas in most applications [26]. Among these applications we quote:

- Satellite communications.
- Command and control.
- The telemetry.
- Portable equipment.
- The feed elements in complex antennas.
- The transmitting antennas used in medicine.
- Satellite navigation receivers.

II. Characteristic parameters of an antenna

II.1. Introduction

The first antennas appeared at the end of the 19th century, at a time when work on electromagnetics experienced considerable development. Since then, their realization has continued to evolve, first, thanks to the scientific progress of electromagnetism, later, under the pressure of numerous technological demands in various fields of application [48]. The current boom in communications requires significant innovations in the design of systems and associated antennas, the forms of which today vary widely depending on the user: mobile telecommunications, satellites, television, radio, identification, communication objects, … Etc. Despite this great diversity, all antennas have in common the transformation of a guided signal into a radiating signal (or vice versa), in a relatively wide electromagnetic spectrum ranging from radio waves to microwave frequencies. The race for innovation in communication systems is currently leading to in-depth studies in the field of antennas.

In this second part of the chapter we present the fundamental principles of antennas, radiate it and the different antenna parameters.

II.2. Definition of an antenna

One of the most accurate definitions of an antenna is given in the IEEE standard for definitions of terms for antennas. According to this standard, an antenna is a means of radiating or receiving radio waves [41]. More concretely, it is a device that receives signals from a transmission line, converts them into electromagnetic waves and broadcasts them in free space when the antenna is in transmit mode. In reception mode, it simply picks up the incident electromagnetic waves and converts them back into signals. Figure 2.1 makes a very simple illustration [40].

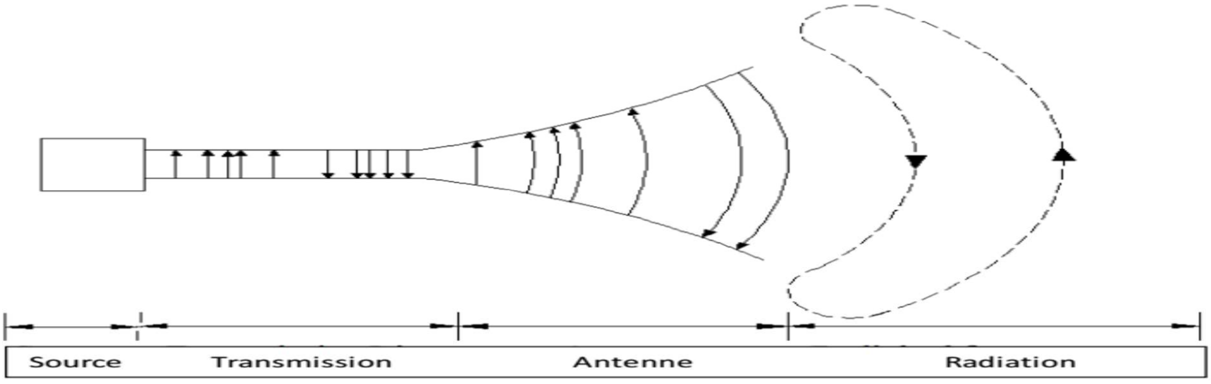


Figure 2.10. *Radiation of an antenna.*

II.3. The role of an antenna

The antenna has several roles, the main ones being:

- Allow a correct adaptation between the radio equipment and the propagation medium.
- Ensure the transmission or reception of energy in preferred directions
- Transmit information as faithfully as possible [38].

If we consider a simplest wireless communication system, it would be composed of a transmit block and a receive block. These two blocks would be separated by a propagation channel in which the transmitted signal passes before being received as shown in the figure 2.10.

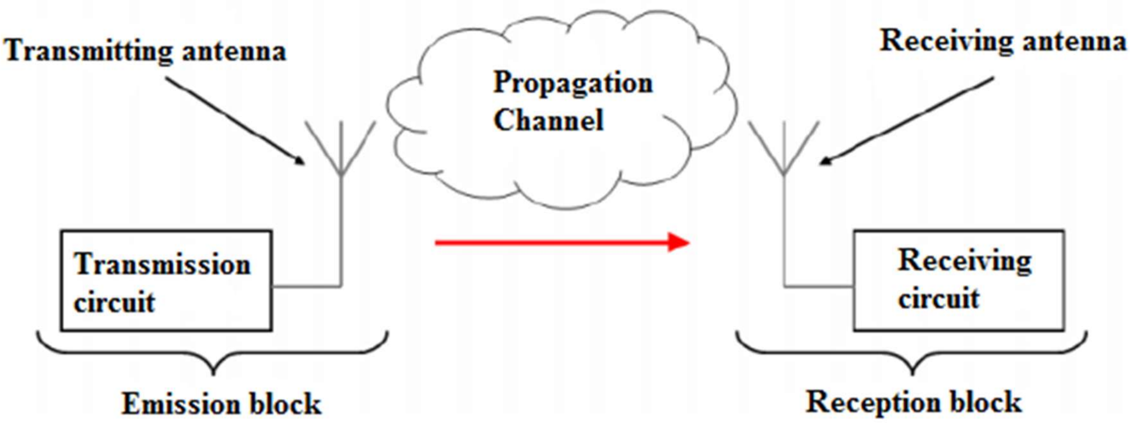


Figure 2.11. *Schematic diagram of a radio communication system.*

II.3.1. Emission block

At the level of the transmitting block, the transmitting circuit supplies at its output a high frequency current, generally modulated, which will be transformed into electromagnetic waves capable of propagating in the channel, it is the transmitting antenna which fulfills this role.

II.3.2. Reception block

Conversely at the level of the reception block, when the waves reach the receiver, it is the reception antenna that has the role of transforming them into current capable of being processed by the reception circuit.

Thus, an antenna can be defined by its function: it is a passive transducer which converts the electrical quantities of a conductor or a transmission line (voltage and current) into electromagnetic quantities in space (electric field and magnetic field) and vice versa. An antenna can therefore either be used for reception or transmission; moreover, as the theorem of reciprocity of Lorentz [37] shows it, the whole of the characteristics of an antenna are identical whether the antenna is used as transmitting or receiving antenna. This is very interesting because it means that a communicating object having a transmitting part and a receiving part can use the same antenna [32].

II.3.3. Reciprocity

In most cases, an antenna can be used for reception or transmission with the same radiating properties. It is said that its operation is reciprocal. This is a consequence of the reciprocity theorem. Due to the reciprocity of the antennas, there will hardly ever be a difference between the radiation in transmission or reception. The qualities that will be announced for an antenna will be announced in the two operating modes, without this being specified in most cases [30].

In the following parts we will specify what are the parameters which exhaustively define an antenna.

II.4. Characteristic parameters of an antenna

Many parameters are used to describe the characteristics and antenna performance such as input impedance, reflection coefficient, the directivity, the gain, the yield, as well as the radiation patterns ... etc [26].

II.4.1. Input impedance

The input impedance of an antenna is defined as the ratio between the voltage and current at the antenna terminals or as the ratio between the appropriate components of the electric and magnetic fields. The expression of the input impedance of an antenna $\boldsymbol{Zan}$ breaks down into a real part $\boldsymbol{Rant}$ and an imaginary part $\boldsymbol{Xant}$ and is written as follows:

$$\boldsymbol{Z_{ant}} = \boldsymbol{R_{ant}} + \boldsymbol{jX_{ant}} \tag{2.4}$$

$\boldsymbol{Zant}$: Characteristic impedance of the supply line.

The real part of the impedance $\boldsymbol{Rant}$ groups together a part due to the ohmic and dielectric losses of the materials and the radiation resistance of the antenna and it is written as follows:

$$\boldsymbol{R_{ant}} = \boldsymbol{R}_{\text{losses}} + \boldsymbol{R_{ray}} \tag{2.5}$$

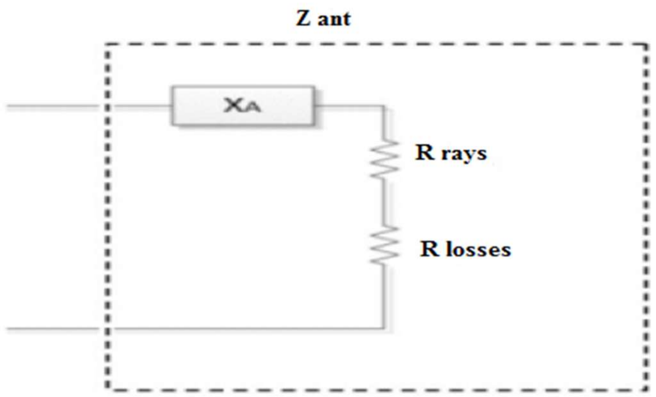


Figure 2.12. *Representation of the antenna impedance [59]*

To ensure that power has been transferred from power to the antenna, it is necessary to have an impedance adaptation. The maximum power transfer is obtained when the impedance of the supply line Zc is equal to the combined impedance of the antenna and as the reflection coefficient ($S11$) is a function of the frequency then $Zant$ also varies with the frequency. This input impedance as a function of $S11$ is given by the formula [28] [27]:

$$Zant = Zc\frac{1+S11}{1-S1} \tag{2.6}$$

II.4.2. Radiation resistance

For antennas, the total transmitted power <Pt> is related to the peak current (Using the effective current $I_{rms} = I_{crète}/\sqrt{2}$, we obtain $< P_t > = R_{ri} I^2{}_{inr}$).

Γ_{in} measured at the antenna input via the radiation resistance seen at the input R_{ri} which is not a physical dissipative resistance :

$$< P_t > = \frac{1}{2} R_{ri} I^2{}_{in} \tag{2.7}$$

This resistance is added to that of the joule losses (or losses in general) to form the real part of the antenna's impedance:

$$R_a = R_{ri} + R_{\text{loss}} \tag{2.8}$$

$Rpertes$: is the resistance which causes:

- Ohmic or thermal losses $Rohm$;
- The losses in the dielectric $Rdie$;
- Return losses (ground conductivity) for monopolies $Rsol$.

Resistor Rri is responsible for the radiation of the antenna, because without it no active power supplied to the antenna is emitted. It is therefore advantageous to have it as high as possible to increase the importance of radiated fields.

The symbol Rr is reserved for the radiation resistance, which is calculated from the maximum amplitude of the current distribution on the antenna:

$$< P_t >= \frac{1}{2} R_r I^2_{max} \tag{2.9}$$

If the maximum amplitude is at the terminals, then $R_r = R_{ri}$ [29].

II.4.3. The reflection coefficient and the R.O.S

The reflection coefficient of an antenna represents the ratio of the amplitudes of the incident waves to the reflected waves.

For an antenna of impedance $Zant$, connected to the source by a characteristic impedance line Zc, the reflection coefficient can be defined as follows:

$$S_{11} = \Gamma = \frac{\text{Zant}-\text{Zc}}{\text{Zant}+\text{Zc}} \tag{2.10}$$

With: $Z_c = 50\ ohm$.

The modulus of the reflection coefficient is often expressed in decibel (dB) and is noted | $S11$ | and is defined as follows:

$$|S_{11}|_{dB} = 20log\ (S_{11}) \tag{2.11}$$

The reflection coefficient makes it possible to know the quality of adaptation of an antenna. In fact, the more its module tends towards infinity negatively, the more the antenna is adapted. Often, the resonant frequency of an antenna is that where the reflection coefficient is minimal [30].

In practice, the adaptation is characterized by the modulus of the reflection coefficient or, more often, by the "Stationary Wave Report" (R.O.S.) [34].

When the adaptation is not perfect, the part of the reflected wave is superimposed on the incident wave to form only one wave, called the standing wave. It is defined as the ratio of the maximum and minimum values of the amplitude of the standing wave. The ROS or, in English, VSWR for Voltage Standing Wave Ratio can also be expressed from the reflection coefficient that we have just defined through the expression:

$$ROS = \frac{1+|\Gamma|}{1-|\Gamma|} \tag{2.12}$$

The term TOS (Stationary Wave Rate) can be used in place of ROS.

II.4.4. Resonant frequency and bandwidth

The bandwidth of an antenna therefore defines the frequency range in which the reflection coefficient is less than an arbitrarily set threshold.

Generally, the bandwidth corresponds to the frequency range for which the reflection coefficient is lower by -10dB. But in certain applications, this level can be raised to -6 dB which makes it possible to relax certain constraints when designing an antenna, this is the case, for example, for certain antennas of mobile phone. It is however generally accepted that if the threshold at which the bandwidth is considered is not specified, $\boldsymbol{S11}$ less than -10dB. Figure 2.12 shows the parameter $S11$ of an antenna as a function of frequency and highlights the bandwidth at -10 dB. In this example the bandwidth which is expressed in Hertz (Hz) is 226 Mhz.

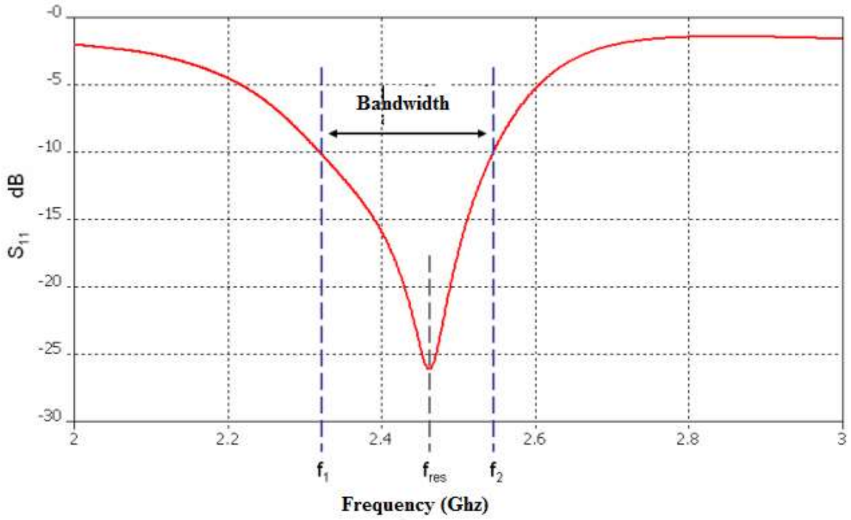


Figure 2.13*. Illustration of the -10 dB bandwidth of an antenna.*

The resonance frequency, $\boldsymbol{fres}$ corresponds to the frequency for which the antenna is best suited, that is to say for which the reflection coefficient is the lowest. On a given bandwidth, it is possible to observe several minima, therefore several resonance frequencies [34].

The bandwidth is defined by the following formula:

$$\boldsymbol{BW} = \frac{\mathbf{f2{-}f1}}{\mathbf{fc}} \tag{2.13}$$

With $f2$ and $f1$ the maximum frequency and the minimum frequency between which the reflection coefficient is less than -10 dB (or even -6dB) and fc the central frequency [61].

In order to compare antenna structures, the bandwidth, BW of an antenna is often expressed as a percentage with respect to the resonant frequency 2.1 [35].

$$\boldsymbol{BP}\ (\%) = \frac{\mathbf{f2-}}{\mathbf{fc}} \times 100 \tag{2.14}$$

II.4.5. Radiation diagram

The graphical representation of the antenna's characteristic function is called the radiation pattern. The direction of maximum radiation is called the antenna radiation axis. The representation of this function gives the characteristics of radiation in space. Conventionally, we have got into the habit of representing the radiation diagram in two perpendicular planes which are: The E plane and the H plane. The E plane is defined as the plane containing the axis of the antenna and the electric field. The H plane is defined as the plane containing the axis of the antenna and the magnetic field.

Certain three-dimensional representations have the advantage of showing all the directions of radiation in space (Figure 2.13) but hardly allow a quantitative appreciation. The figure is in logarithmic coordinates. This makes it possible to better see the details for the low values, in the lateral lobes.

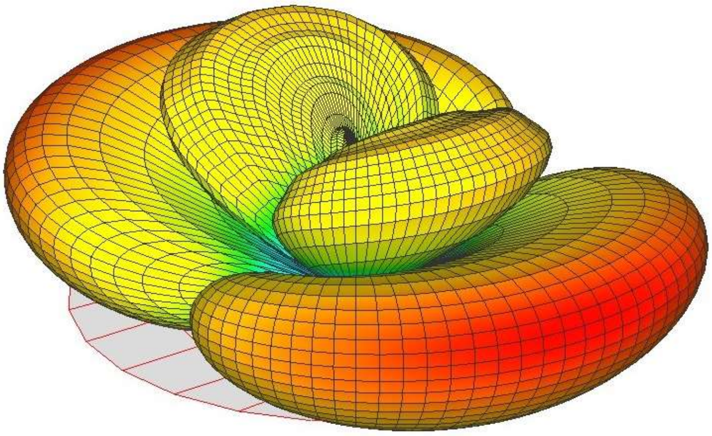


Figure 2.14. *Example of 3D radiation diagram.*

The radiation diagram, generally in logarithmic coordinates, is presented either in rectangular coordinates or in polar coordinates, in the two perpendicular planes (E and H).

II.4.6. Opening angle

The beam width characterizes the width of the main lobe. The 3 dB $2\theta 3$ opening angle represents the portion of the space in which most of the power is radiated. It is the angle between the 2 directions around the main lobe where the radiated power is equal to half of the radiated power in the direction of maximum radiation.

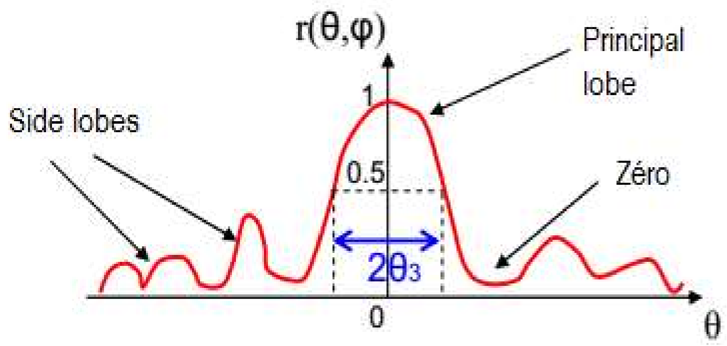


Figure 2.15. *Radiation diagram and opening angle.*

Other quantities are used to characterize the opening of an antenna and its ability to focus the radiated power in a given direction. We find the angle between the direction of maximum radiation and the first zero. To characterize the vertical direction of the main lobe, we use the elevation angle. In practice, this angle must be adjusted to any antenna installation by adding a tilt to it.

This can be controlled mechanically (adjustment at installation of the angle made by the antenna with the vertical) or electrically (by phase control of the excitations of each radiating element of the antenna [35].

II.4.7. Directivity

The directivity of an antenna is the ratio of the radiated power per unit of solid angle in the direction ($\boldsymbol{\theta}$, $\boldsymbol{\varphi}$) to the power that the reference isotropic source would radiate per unit of solid angle for the same total radiated power [36].

$$(\boldsymbol{\theta}, \boldsymbol{\varphi}) = \boldsymbol{4\pi}\,\frac{\mathrm{P}(\theta,\varphi)}{\mathrm{PR}} \qquad (2.15)$$

($\boldsymbol{\theta}$, $\boldsymbol{\varphi}$) : The radiated power per unit of solid angle (θ, φ).

P_R : Total radiated power.

The directivity indicates in which directions the power density is better or less good than that of the isotropic antenna [39].

II.4.8. Gain

The power radiated by an antenna generally varies depending on the direction considered. The gain of an antenna in one direction ($\boldsymbol{\theta}$, $\boldsymbol{\varphi}$) is the ratio of the power radiated in this direction P ($\boldsymbol{\theta}$, $\boldsymbol{\varphi}$) to the power that the isotropic reference source would radiate per unit of solid angle with the same power and it is expressed by (2.16) [44] [40].

$$(\boldsymbol{\theta}, \boldsymbol{\varphi}) = 4\boldsymbol{\pi}\,\frac{\mathrm{P}(\theta,\varphi)}{\mathrm{PR}} \tag{2.16}$$

$\boldsymbol{P_A}$ **:** The power of an antenna.

The relation between the gain and the directivity of an antenna is given by the following equation [43].

$$(\boldsymbol{\theta}, \boldsymbol{\varphi}) = \boldsymbol{\eta}(\boldsymbol{\theta}, \boldsymbol{\varphi}) \tag{2.17}$$

$\boldsymbol{\eta}$ **:** The efficiency.

II.4.9. The efficiency

Let $\boldsymbol{PA}$ be the feed power of an antenna. This power is transformed into a radiated power $\boldsymbol{PR}$. In the direction of emission, the radiated power is less than the supply power [65] [66]. The antenna is an imperfect transformer. There are losses during energy transformation, as in any system. The efficiency of the antenna is defined by :

$$\boldsymbol{\eta} = \frac{\mathbf{PR}}{\mathbf{PA}} \tag{2.18}$$

It measures the transformation rate. It is a yield in the thermodynamic sense of the term: $\boldsymbol{\eta} \leq \mathbf{1}$

The efficiency is linked to the losses in the polarization network and in the radiating elements. By comparing equations 2.16-17, we see that the yield links the gain and the directivity [55]:

$$\boldsymbol{P_R} = \boldsymbol{\eta} \cdot \boldsymbol{P_A} \Rightarrow \boldsymbol{G} = \boldsymbol{\eta} \cdot \boldsymbol{D} \tag{2.19}$$

II.4.10. Quality factor

From an electrical point of view, an antenna can be seen as an RLC resonant circuit. The bandwidth BW (bandwidth at 3 dB of the field value) is linked to the quality factor Q of the RLC circuit at the resonance frequency $\boldsymbol{fres}$. The quality factor represents the amount of resistance present during resonance (for a series resonant circuit as shown in equation (2.20).

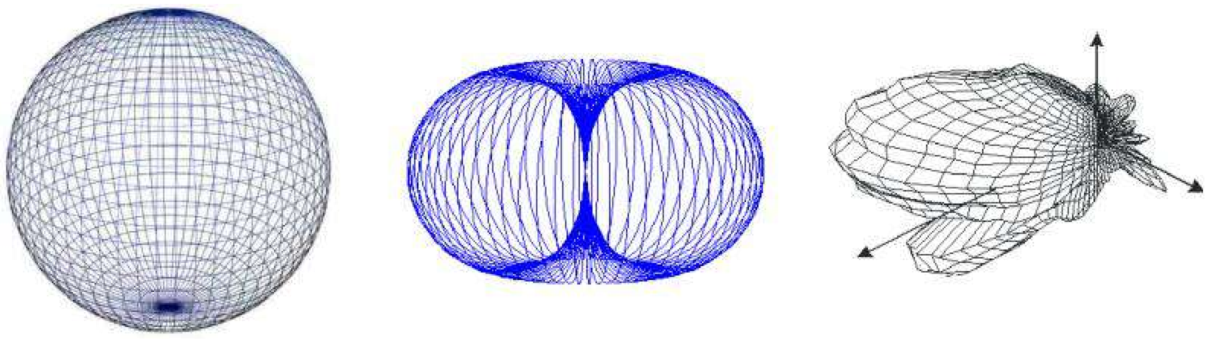
$$\boldsymbol{Q} = \frac{\mathbf{fres}}{\boldsymbol{BW}} \longrightarrow \frac{\mathbf{1}}{\boldsymbol{Q}} = \frac{\mathbf{Rant}}{\mathbf{2\pi fres \cdot Lant}} \tag{2.20}$$

An antenna with a high-quality factor radiates very effectively at the radiation frequency over a narrow frequency band, which can limit out-of-band interference. However, if the bandwidth is too narrow, any signal sent or received near the terminals of the operating frequency band will be attenuated. An antenna with a low-quality factor is considered to be broadband if the upper frequency $\boldsymbol{f2}$ is at least about twice the lower frequency $\boldsymbol{f1}$ [44].

II.4.11. Polarization

Polarization is a very important parameter in the characterization of an antenna [49], it is defined as being the orientation of the electric field of an electromagnetic wave. Polarization is generally described by an ellipse. Linear polarization and circular polarization are two special cases of elliptical polarization. The initial polarization of a radio wave is determined by the antenna.

With linear polarization, the electric field vector stays in the same plane all the time. The electric field can leave the antenna in a vertical orientation, a horizontal orientation or in an angle in between. Vertically polarized radiation is slightly less affected by reflections in the transmission path and the lower radiation angle. Omnidirectional antennas always have vertical polarization. With horizontal polarization, such reflections cause variations in the strength of the received signal. Horizontal antennas are less sensitive to interference from humans because they are generally vertically polarized [50] [51].



a - Isotropic **b - Omnidirectional** **c - Directive**

Figure 2.16. *Examples of antenna radiation diagram.*

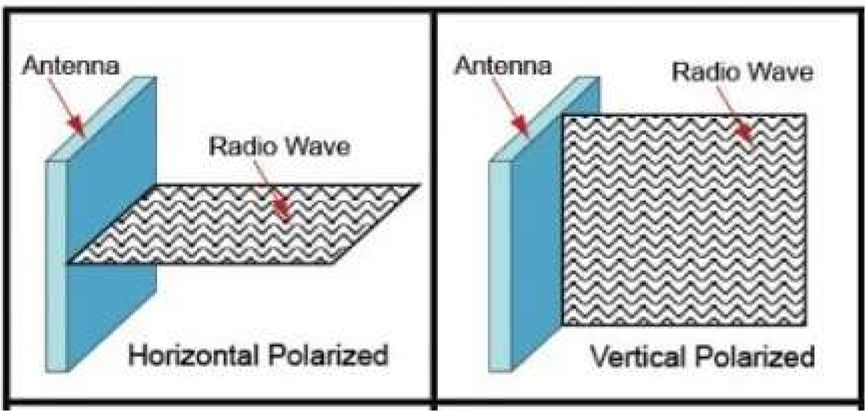


Figure 2.17. Representation of vertical and horizontal polarization.

II.4.12. Noise temperature

In telecommunications, the strength of a received signal is not sufficient to deduce the signal quality or the risk of binary error if it is a digital signal. Indeed, it is necessary to know the signal to noise ratio. The noise level fixes the reception threshold. Although the receiver introduces a significant amount of noise (taken into account through the noise figure or noise figure), we will ignore its effect in this course and we will limit ourselves to the noise available at the output of the antenna.

In a receiver, the antenna is the source of noise placed on its input. This noise can come from electromagnetic interference, especially if it exists on the antenna operating band. But although the antennas are not broadband, they remain capable of coupling a non-negligible part of the out-of-band signals. Consider the case where there is no interference. The noise will come from antenna losses and radiation from the environment. The noise depends on the antenna radiation pattern, the direction from which the noise comes and the state of the surrounding environment. We define the noise power of an antenna PN by the following relation.

$$\boldsymbol{P_N = KT_{ant}B} \tag{2.21}$$

Where 'k' is the Boltzmann constant (k = 1.38 · 10−23 J.$K - 1$), B the frequency band considered and $Tant$ the noise temperature of the antenna. The antenna noise temperature is therefore a proportionality factor that characterizes the noise from the environment and picked up by the antenna. It depends on the temperature of the objects in the antenna radiation pattern. The noise temperature of a terrestrial antenna can therefore be divided into two: the contribution of the sky, which presents a low temperature and varying with the state of the sky, and that of the Earth whose noise temperature is close to its temperature. ambient.
The antenna noise temperature is given by the following equation [50]:

$$\boldsymbol{T_{ant}} = \frac{T\ earth}{4\pi} \iint \text{earth}\ \boldsymbol{G\ (\theta,\varphi)\ d\Omega} + \frac{1}{4\pi} \iint \text{earth}\ \boldsymbol{T}_{\text{sky}}\ \boldsymbol{(\theta,\varphi)\ G\ (\theta,\varphi)\ d\Omega} \tag{2.22}$$

III. UWB & Multiband antennas

III.1. Ultra-Wide Band patch antennas (UWB)

Ultra-wide band communications are different from other communication techniques because they use pulses (Radio Frequency) extremely narrow to communicate between transmitters and receivers. The use of pulses to short duration as a module for communications directly produces a width of very large band and offers several advantages, such as high speed, security, robustness to interference and coexistence with usual radio services [55].

III.1.1. Uses of the ultra-wide band (UWB)

The United States is the first country to regulate the use of Ultra-wideband. In February 2002 the FCC (*Federal Communications Commission*) has limited UWB signal emission levels ($EIRP = -41.3\ dBm/MHz$) for a frequency spectrum from 3.1 $GHz\ to$ 10.6 GHz [35].

Figure 3.1 shows UWB systems compared to other radio systems from the point of view of the power spectral density emitted [36]. The recent boom in ultra-wideband communications requires antennas specially adapted for this technology [52].

The Ultra-Wide Band was released by the FCC in February 2002. A signal is saying ultrawide band if [4]:

- Its bandwidth is at least 500 MHz ($at\ -10\ dB$).
- Its relative bandwidth is higher to 0.2 (20%).

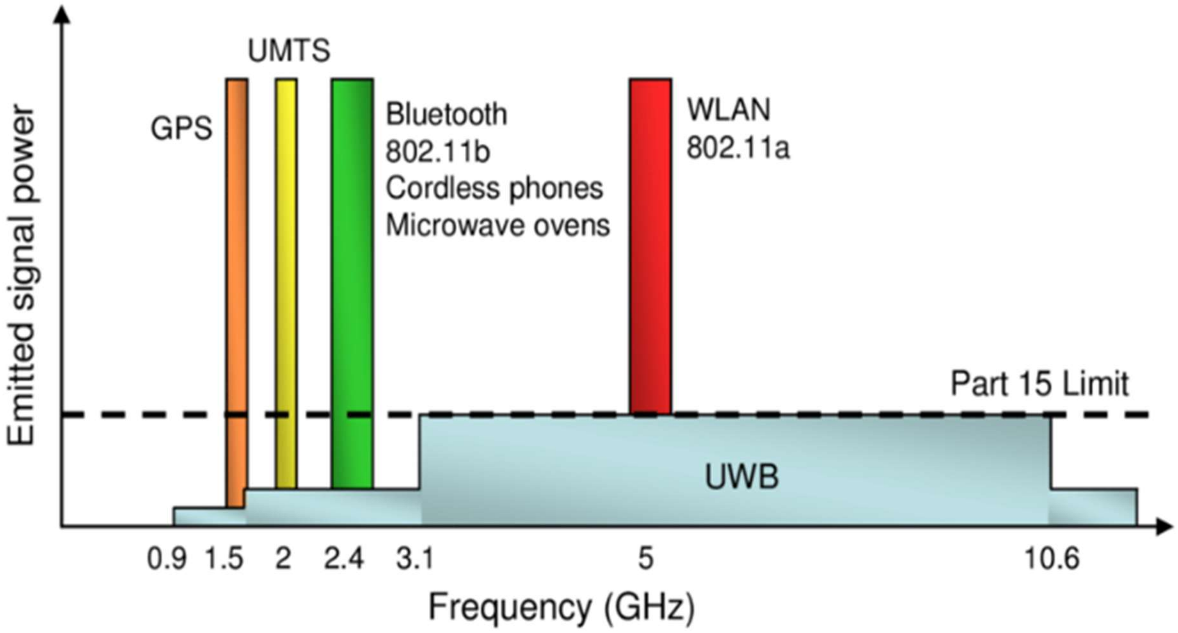


Figure 2.18. *UWB spectrum overlaying existing narrowband systems.*

III.1.2. Advantages and disadvantages of Ultra-Wide Band

UWB technology has several advantages over narrowband systems like [58], [59]:

- High speed for a Wireless Local Area Network (WLAN).
- Good penetration capacity in walls and obstacles.
- High performance in multipath channels.
- Ability to operate with low SNR.

One of the drawbacks of using this communication technique is the fact that the frequencies used are already used by other systems, which makes possible the existence of interference [53].

III.2. Application of Ultra-Wide band [68]

The main features of the extremely large UWB bandwidth, low power, short range communication at high speed, robustness against fainting, multipath immunity, multiple access possibilities, transmitters receivers at a reduced price and precise positioning, motivate several applications of this technology. So far, UWB technology has been mainly applied to devices applications (particularly radar). Applications are generally classified into six groups to know:

- Ad-hoc network management,
- Wireless sensor networks,
- Radio frequency or RFID identification,
- Consumer electronics,
- Location,
- Medical applications.

II.3. The structure of antenna with a wide band

Coplanar structures and structures that have a partial ground plane given a wide bandwidth compared to simple structures.

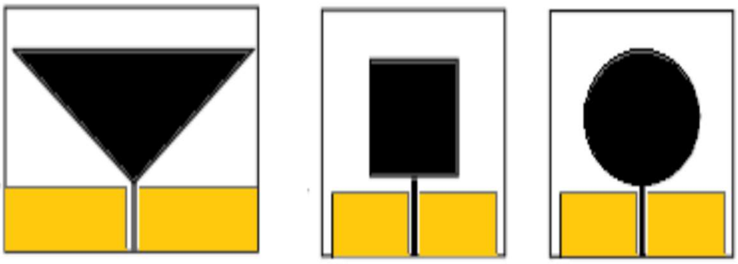


Figure 2.19. *The different forms of coplanar patch antenna*

- **Coplanar structures:** is a structure having the plan and the patch printed on the upper side of a substrate.
- **Structures that have a partial ground plane:** is a structure with the plane of partial mass printed on the underside of the substrate.

III.3.1. Classification of UWB antennas

UWB antennas can be divided into four different classes, depending on their shapes and specificities:

- **Frequency independent antennas**

In theory, the frequency independent antennas are composed of elements capable of being deduced from each other by homothety. They have the particularity to present a radiation diagram, an input impedance as well as a virtually unchanged polarization on an almost infinite frequency band. As an example, for this class of antennas, we can note two main groups. In this case, the equiangular antennas (logarithmic spiral antenna, conical spiral antenna) and log-periodic antennas.

- **Elementary antennas**

In general, the structures of elementary antennas are considered as an evolution of monopoles or simple dipoles. In this category we can mention; the biconical antenna, the discone antenna, as well as the plane monopoles on ground plane.

- **The gradual transition antennas**

The progressive transition antennas are based on the idea that an antenna can be considered as a transition zone between a waveguide or any other feeding system and free space. Vivaldi antennas, which have an elliptical or exponential transition profile, fall into this category.

- **Cornet antennas**

With intrinsic broadband characteristics, the horn antennas are not very dispersive. However, they are bulky and their production cost is high. The Brillouin horn antennas are part of this group of antennas.

III.4. Multiband Antennas

Advances in the multiplication of frequency bands have generated a need crescent of multi-band antennas. Indeed, the use of such antennas has generalized in various modern telecommunications systems.

A multi-band antenna, by definition, is an antenna operating in two or more frequency bands with fairly similar performance in these bands. The operation of an antenna on a frequency band generally results in a "reasonable" adaptation of the antenna for all frequencies in the band. This "reasonable" adaptation is defined by a reflection coefficient or a wave rate stationary (TOS) at the input of the antenna lower than a fixed value. (Currently: -10 dB, -15 dB, or -20 dB for the reflection coefficient and 2, 1.5, 1.2 for the TOS) [49].

4.1. Advantages and disadvantages of Multiband

A multi-band antenna is a much more selective antenna, because it only allows the passing of the bands of interest while playing the role of a filter. Another advantage of multi-band antennas is the possibility of using independent radiating elements for each band.

Thus, it is easy to vary the coverage area of one of the bands without modifying the covers of the other bands of the antenna. The variation in band coverage is obtained by a variation of the radiating element responsible for this band [41].

These advantages do not prevent multiband antennas from having several disadvantages which may be mentioned:

- Weak mastery of operating frequencies.
- Limited number of bands to cover.
- More sensitive to errors of manufacturing.

4.2. The difference between UWB and Multiband antennas

	Multiband antennas	**Ultra-wide band antennas**
Strong points	✓ High selectivity ✓ Simplified post processing	✓ Relatively easy design ✓ Less sensitive to errors of manufacturing ✓ The antenna can also be used for other applications contained in broadband covered
Weak points	○ Weak mastery of operating frequencies ○ Limited number of bands to cover ○ More sensitive to errors of manufacturing	○ Impedance adaptation often delicate across the width of the bandaged ○ Post treatment necessary for separate the bands ○ Limited bandwidth ○ Low directivity

Table 3.1. *Strengths and weaknesses of multi-band and wide-band antennas*

4.3. Classification of multiband antennas

Multi-band antennas are generally classified into two categories:

4.3.1. Multi resonators

In this kind of antenna, we use either multilayer plates stacked in a way each plate is designed to radiate at a well-determined frequency or by printing more resonators on the same substrate [73].

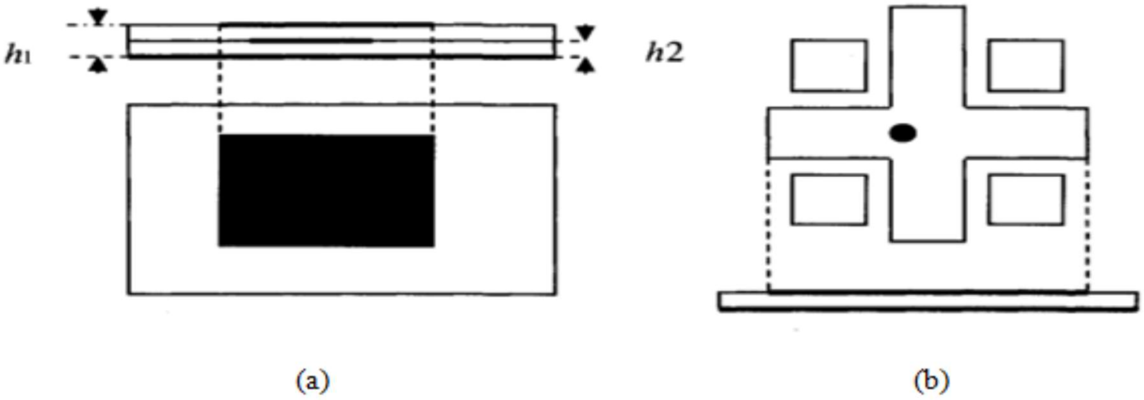


Figure 2.20. *Types of antennas with multi resonators.*

4.3.2. Reactive load antennas

The most popular technique for achieving dual frequency behavior is the introduction of a reactive load applied to the microstrip plate, including stubs [59], pins, capacitors and slots. Using the reactive charge approach, we can modify the resonant mode of the radiant plate.

Using the reactive load approach, we can modify the resonant mode of the radiant plate. This confirms that the use of a single power supply for the two frequencies on a single element of radiation is doable.

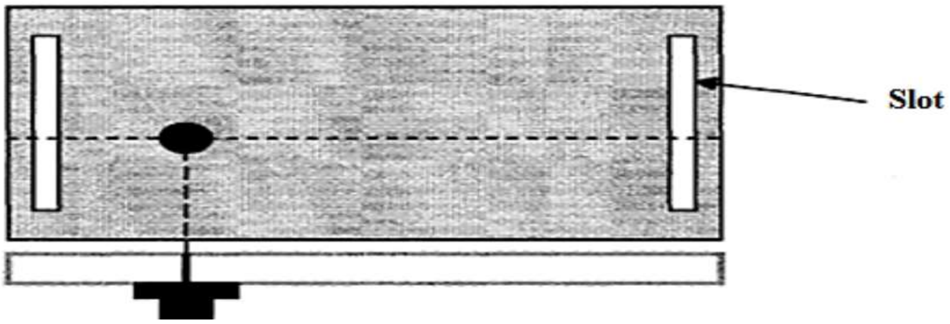


Figure 2.21. *Double slit antenna fed by a probe.*

4.4.Application of multiband antennas

The multiband antenna is very well suited for applications such as wireless communications system, cellular phones, pagers, Radar systems and satellite communications systems.
Radio navigation systems generally need multiband antennas high performance with circular polarization [55].

Most reported multiband antennas are for WLAN/WiMAX applications. Several promising multiband antennas have been reported for applications in GPS/WiMAX/WLAN LTE/GSM/UMTS and WLAN/WiMAX, TD-LTE/WLAN/WiMAX, and C-band/WLAN/International Telecommunications Union (ITU). Other applications of the multiband antenna are for X-band satellite communication (7.25–7.75 GHz) [48].

III.5. Effects of slots on microstrip patch antenna

The microstrip slot antenna was invented by Alan Blumlein in 1938. Slot antennas are antennas used in the frequency range of about $300\ MHz\ to\ 25\ GHZ$. They are commonly used as arrays of waveguide feeds in navigation radars. As the demand for reliable wireless communications continues to grow, the demand for effective use of the electromagnetic spectrum is rising. However, older large phased array antennas also use this principle because slot radiators are a very inexpensive method for frequency scanning arrays.

The microstrip slot antenna has a simple structure. It consists of a microstrip feed that couples electromagnetic waves through the gap above and radiates them. The microstrip slot antenna provides better isolation between the material being fed and the material being tested to the microstrip feed microstrip antenna. They are more flexible when integrated with other active and passive devices in hybrid MIC and MMIC designs. In addition, they only need to insert a quarter-wave-thick foam and mirror to produce an omnidirectional radiation pattern. We have found that slot antennas can be used in fixed stations, satellite ground stations, and before proper installation, slot antennas can also be used in microwave movement [42].

5.1. Effect of slot on different parameters of microstrip patch antenna

5.1.1. Effect of slots on bandwidth

The bandwidth is defined according to the radiation parameters. It is defined as the frequency range within which the radiation parameters (eg gain, HPBW, side lobe level) are within the specified minimum and maximum limits.

According to the voltage standing wave ratio or input impedance changes with frequency or radiation pattern. The VSWR or impedance bandwidth of a microstrip patch antenna is defined as the frequency range that matches the feeder within a specified range. The bandwidth of the microstrip patch antenna is defined as the frequency range that matches the feeder within the specified range. The bandwidth of the microstrip patch antenna is inversely proportional to it.

$$\textbf{Bandwidth}= \frac{\mathbf{VSWR-1}}{\mathbf{Q\sqrt{VSWR}}} \tag{2.23}$$

The bandwidth is usually specified as the frequency range where VSWR is less than 2. Sometimes VSWR is required in strict applications. The bandwidth of the antenna will increase as the gap increases. These structures are periodic in nature, prohibiting all electromagnetic waves from propagating surface waves in a specific frequency band called the band gap, thus allowing other control over the behavior of the electromagnetic waves instead of the conventional guiding/filtering structure [50].

5.1.2. Effect on slots on the gain

Gain relates the strength of an antenna in a given direction to the strength produced by a hypothetical ideal antenna that radiates equally or isotopically in all directions without loss. By using a substrate with a high dielectric constant and slits of different shapes, we can increase the gain of the antenna [47].

5.1.3. Effect of slots on return loss

Return loss is the difference between forward power and reflected power in db. It is usually measured at the input of a coaxial cable connected to an antenna. If the power transmitted by the source is Pt and the power reflected back is Pr then return loss is given by Pr divided by Pt.

For maximum power transfer the return loss should be as small as possible. This means ratio Pr/Pt should be small as possible. For example, a return loss of $-40\ dB$ is better than one of $-20\ dB$.

$$\boldsymbol{RL = -20Log|\Gamma|\ (db)} \tag{2.24}$$

$|\ \Gamma\ |$ is reflection coefficient and it is given as $|\ \Gamma\ | = \frac{\boldsymbol{Pr}}{\boldsymbol{Pt}}$

Where,

P_R = Radiated power.

P_T = Transmitted power.

Z_L = Load impedance.

Z_0 = Characteristic impedance.

Choosing the feeding technology of the microstrip patch antenna is an important decision, because it will affect the bandwidth, return loss, VSWR patch size and Smith chart. Using double-slot or double-slot stacking patch technology can reduce the return loss by increasing the length and width of the slot antenna, thereby obtaining better return loss [80].

5.1.4. Effect of slot on size of antenna

With the help of slot size of microstrip patch antenna is reduced. This effect can be done by changing the path of current. When slots are cut into patch current is changed. Current travels extra patch as compare to the without slot microstrip patch antenna [56].

III.6. Conclusion

In the first part of this chapter, we briefly presented the microstrip antennas. We talked about their description, the excitation techniques, the operating principle, the phenomenon of surface waves. After discussing the different methods of analysis, we discussed the pros and cons. Finally, the study of these parameters is important and makes it possible to design an antenna according to its applications.

In the second part of the chapter we set out to define what an antenna was, the role of an antenna, then we also presented their main characteristic parameters such as the input impedance, radiation resistance, the resonant frequency and the bandwidth as well as the directivity, the gain, the efficiency and the quality factor. We concluded this chapter with the noise temperature.

In the last part of this chapter, we have presented UWB antennas and multiband antennas; and we have given a small comparison between the strong points and the weak points of the two types; while mentioning the applications of both. We have seen again the effect of slot on microstrip patch antenna.

CHAPTER 3 :

Design and simulation of the proposed antenna

I. Introduction

Many designs have been studied and reported to improve the characteristics of the antenna. In this chapter, a new design of multiband Microstrip patch antenna is proposed from a simple rectangular patch antenna with a low gain and ultra-wide band to satisfy multiple bandwidths covering different frequency ranges for WLAN and X-bands.

The bandwidth has improved by adding slots and by fine tuning some parameters to reach the best possible results, then a metamaterial antenna design with the same parameters is compared with the first metallic one.

This chapter is divided in four sections. The first one is dedicated to present the dimensions of the reference and the proposed antennas followed by its simulation results. In the second section we refine the metamaterial antenna so it gives us results close to that of the conventional one and hence use it to obtain a controllable antenna. We describe also the Metamaterial unit cell. In the third one we present a comparison of a metamaterial antenna with the same parameters with the first metallic one.

Finally, in the section four is conclusion. The simulation is carried out using the simulation software HFSS (high-frequency structure simulator), effect parameters of the metamaterial unit cell are calculated using MATLAB, and graphs are plotted using the software ORIGIN.

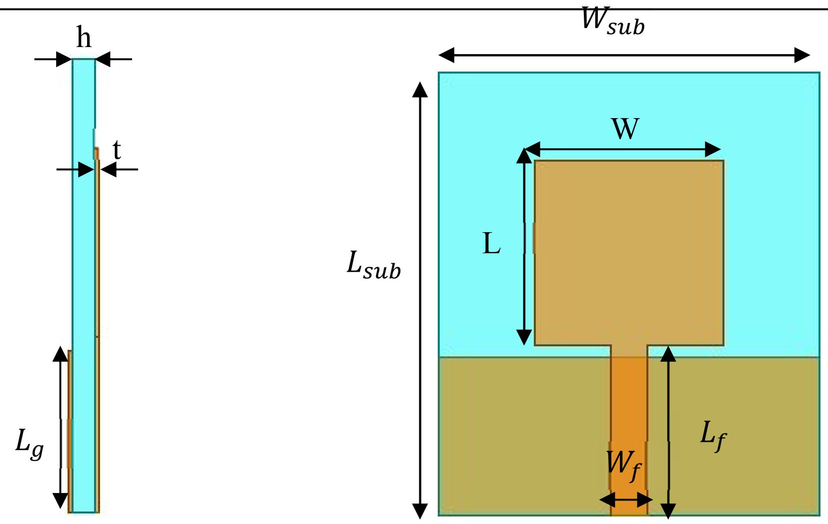
II. Reference UWB rectangular patch antenna design

II. 1 The metallic microstrip antenna

II.1.1- The reference metallic Microstrip antenna

The reference microstrip patch antenna used in this work is taken from an article published in 2015 by the Journal of King Saud University.

It has a width $W = 15\,mm$, a length $L = 14{,}5$ mm, and a thickness $t = 0{,}017\,mm$, fed by a transmission line of length $L_f = 13{,}5\,mm$ and width $W_f = 2{,}85\,mm$. This antenna is built on FR4_epoxy substrate type with a dielectric constant $\varepsilon_r = 4{,}4\,mm$, $tan\,\delta = 0{,}02\,mm$,a length $L_{sub} = 35\,mm$, a width $W_{sub} = 30\,mm$, and a thickness $d = 1{,}6\,mm$, this latter limited at the bottom with a ground plane covering just part of the substrate that represents by length $L_g = 12{,}5$ mm ,the antenna dimensions are shown in $\boldsymbol{figure\ 4.1}$ a and b.[57]

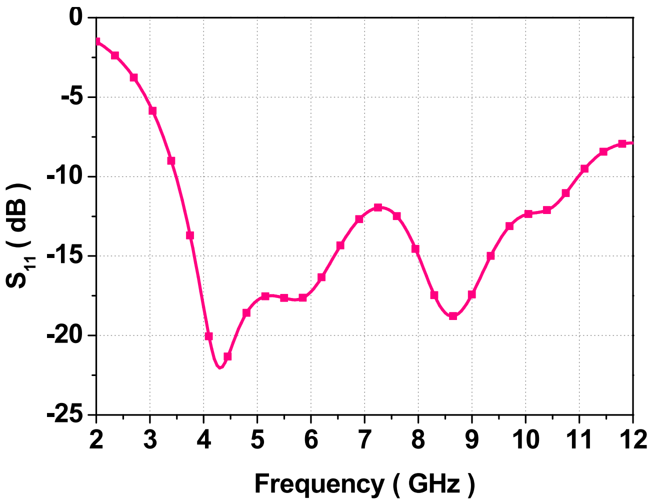


(a) (b)

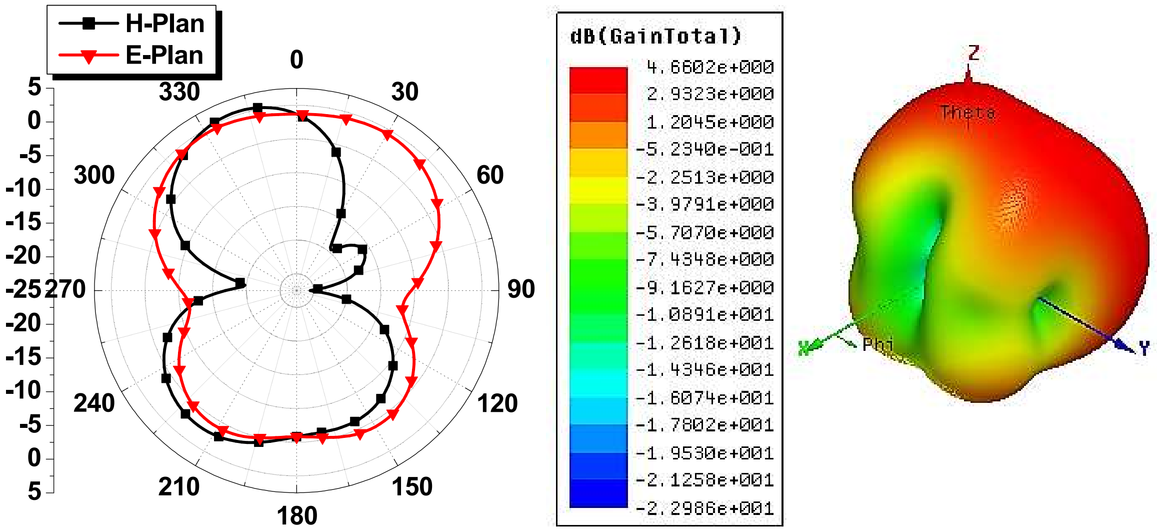
$\boldsymbol{Figure\ 4.1}$: The reference antenna: (a) side view, (b) full view.

The reflection coefficient of the metallic antenna is shown in $\boldsymbol{Figure\ 4.2}$,The frequency response at $-10\ dB$ can cover a $7.5\ GHz$ ultra-wide band which varies from $[3.5\ GHz$ to $11\ GHz]$. The variation of simulated $S11$ as a function of frequency in the band $[2, 12]\ GHz$ shows that this structure has two resonant frequencies: $f_{r_1} = 4.3$ GHz and $f_{r_2} = 8.65$ GHz.

The polar and 3D representation of the radiation pattern shown in $\boldsymbol{Figure\ 4.}2$, where the antenna exhibits a gain of $4.66\ dB$ at the frequency $f\ = 7.8\ GHz$.



$\boldsymbol{Figure\ 4.}$ 1: The reflection coefficient of the metallic patch antenna



(a) (b)

Figure **4.** 2: Radiation pattern of metallic antenna with (a) polar, and (b) 3D representation at 7.8 *GHz*

The antenna must be improved to obtain an antenna with an ultra-wide band and better resonant frequencies, for that we propose an improvement by adding 4 notches at the edges.

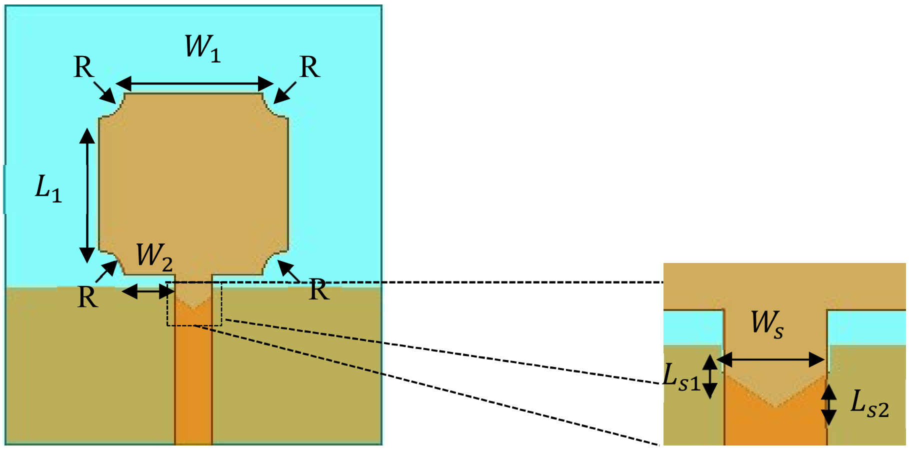
II. 2 Enhanced conventional metallic microstrip antenna

In order to improve the bandwidth and matching of the antenna we will cut notches at the four corners of the patch. The notes have the form of quarter circle of radius R. Also, we add a slot in the ground plane as shown in figure 2-b. All antenna dimensions are represented in ***Table*** **4. 1**.

Table **4. 1**: Proposed antenna dimensions

Parameters	Values (mm)
R	3
W_s	3
L_{s1}	0.75
L_{s2}	1
W_1	9
L_1	8.5
W_2	6,075

The cutting notches at the bottom of the radiator increase the distance between the patch and the ground plane, thereby adjusting the capacitive coupling between them. The notches at the upper corner of the patch can tune the inductive part of the antenna, which can cancel the capacitive coupling between the ground and the patch, thereby obtaining purely resistive input impedance. Adding slots in the ground plan improve the impedance matching. The slots in the ground plane counteract the capacitive effects through the inductive nature of the patch thereby obtaining almost pure resistance input impedance [46].



(a) (b)

Figure **4.**3: (a) Proposed antenna, (b) slot part zoom.

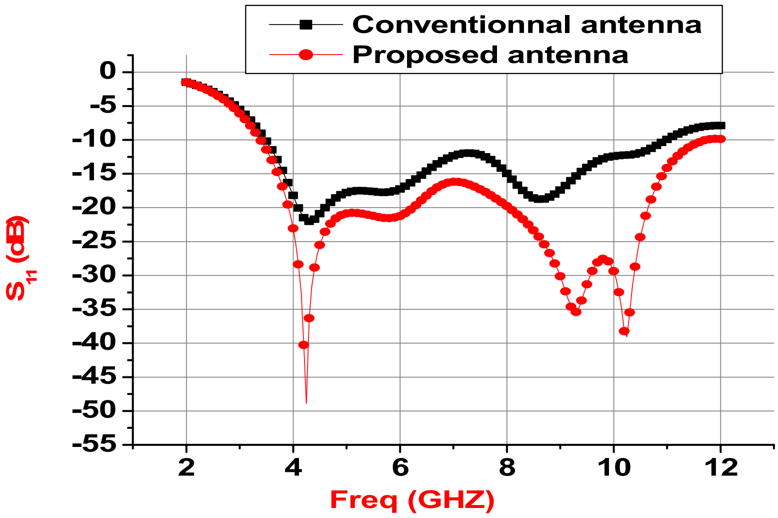
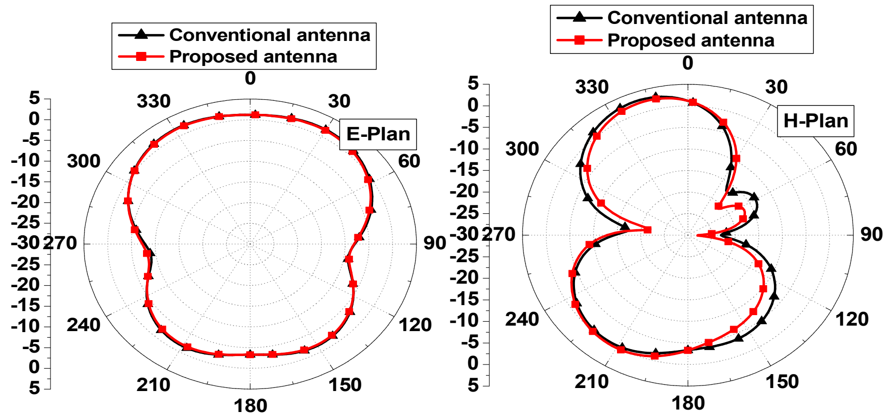


Figure **4.**4: Reflection coefficient comparison between conventional and proposed antennas

Note: the conventional antenna is the reference one.



(a) (b)

***Figure* 4.5**: Radiation pattern comparison between conventional and proposed antennas with: (a) E-plan and (b) H-plan at $f = 7.8\ GHZ$

***Figure* 4.5** indicates that the enhanced metallic microstrip antenna offers an 8.4 GHz ultra-wide bandwidth [3.4 – 11.7 GHz] centered on 7.8 GHz. At this frequency, the antenna exhibits a gain of 4.80 dB. We note that adding notches in the antenna structure improves the impedance matching. at the higher frequency band more than in the lower band.

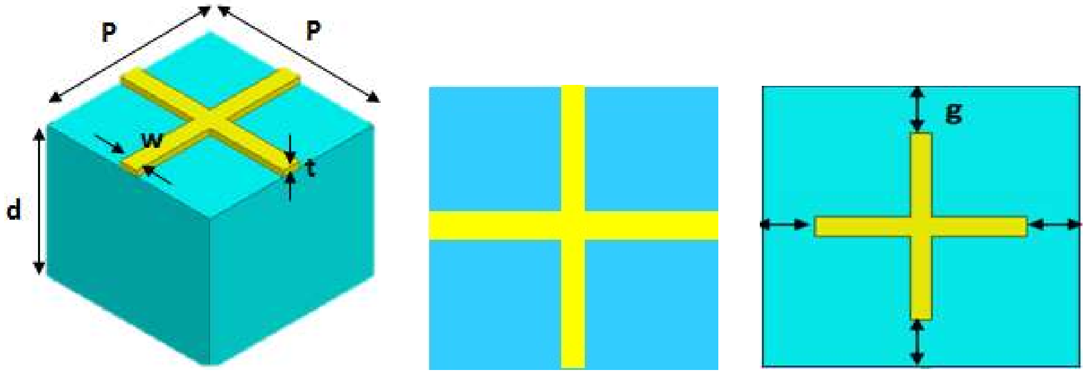
We will tack as reference antenna the enhanced metallic microstrip antenna depicted in ***figure* 4.4**, and it will be mentioned as “conventional antenna”.

III. Metamaterial unit cell description

The metamaterials are artificial materials, which are mixture of the more of one natural material, formed and tailored to respond to desired electromagnetic properties. It behaves like a homogeneous material if the unit cell has dimensions very smaller than the working wavelength. An arrangement periodic of unit cells in space constitutes the electromagnetic waves propagation is allowed.

We are interested to design an agile metamaterial unit cell controlled by an external switching system which exhibits two different behaviors depending on the switches states (ON or OFF).

The unit cell is made of copper cross like conductor and has a period P which is much smaller than the wavelength. The cross as conductor is printed on FR4_epoxy dielectric substrate with $\varepsilon_r = 4.4$ of thickness d as presented in ***Figure* 4.6 − (*a*)**. The four branches of the cross conductor are ended by switches to control the unit cell behavior. This unit cell can have two different behaviors. When the switches are on the OFF state, the metamaterial behaves as a dielectric medium with a refractive index great then the unity and is said disconnected cross type metamaterial. It is used in our design as dielectric material. When the switches are setting on the ON state, the metamaterial behaves as a conductor material with a refractive index close to zero and is said connected cross type metamaterial.



(a) (b) (c)

Figure 4.6: Cross unit cell metamaterial type, (a): full view, (b): connected type, and (c): disconnected type

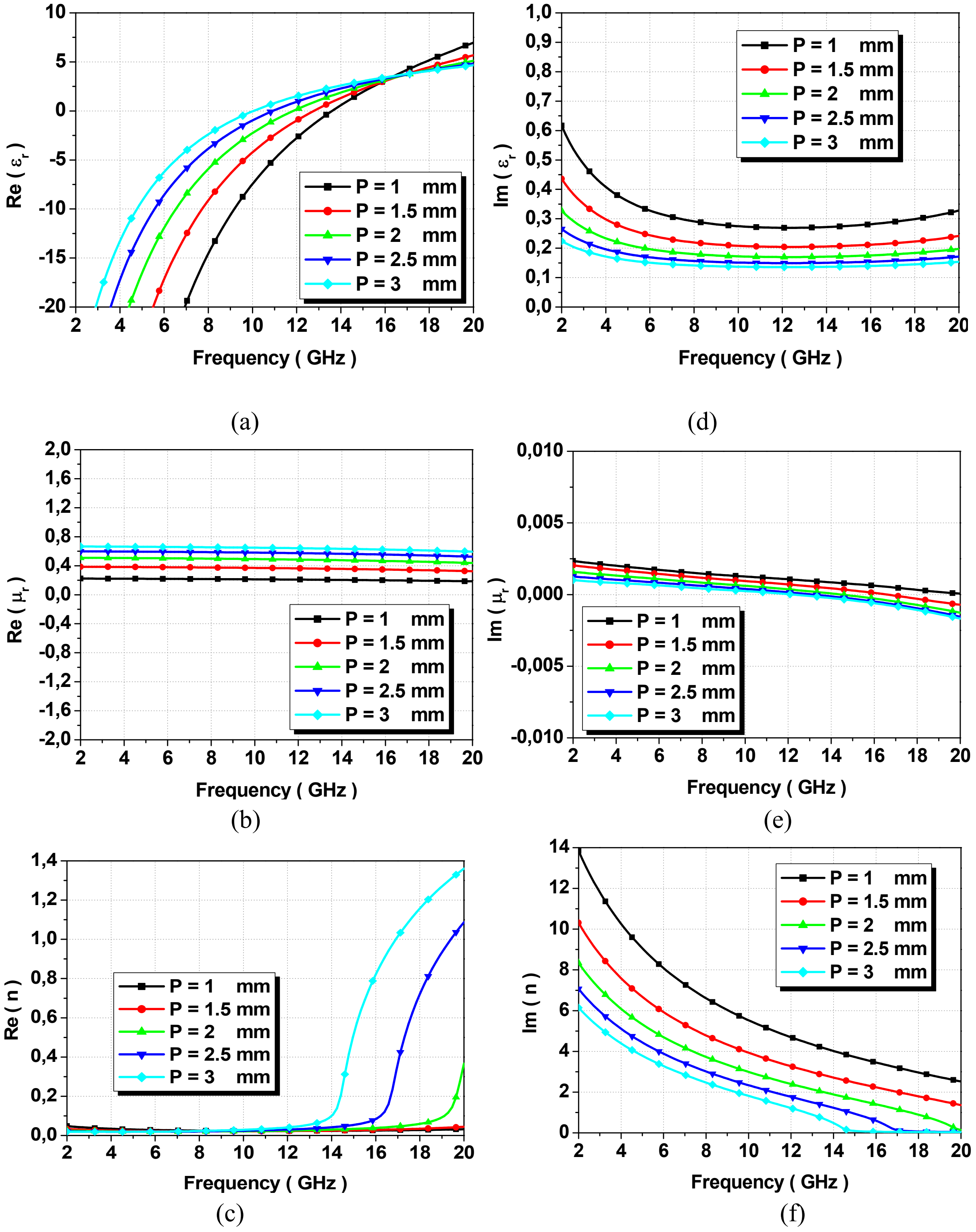
III. 1 Connected unit cell

a. Influence of the period *P*

We study the effect of the periodic length of unit cell which has a major impact on the homogeneity of the metamaterial.

The wavelength of this work is around of $\lambda = 25\,mm$, so the homogeneity hypothesis states that the large cell dimension value must not exceed $P \ll \frac{\lambda}{7}$. In the figure 4.8 the various values of period from $1\ mm$ to $3\ mm$ for the three constitutive parameters: the permittivity, the permeability, and the refractive index are represented.

After representing the permittivity real part in figure 4.8-a , we found that for $P = 3\ mm$, we have a plasma frequency equal approximately to $10\ GHz$ which is the closest to our working range. Where we have a transition point from the negative signal to the positive one, according to the law of Drude and Lorentz, all frequencies which are lower than the plasma frequency are frequencies of the conducting material and the higher frequencies of the Plasma frequency are dielectric materials, which is the aim of this part to find a unit cell connected metamaterial type behaves like a conducting material.



(a) (d)

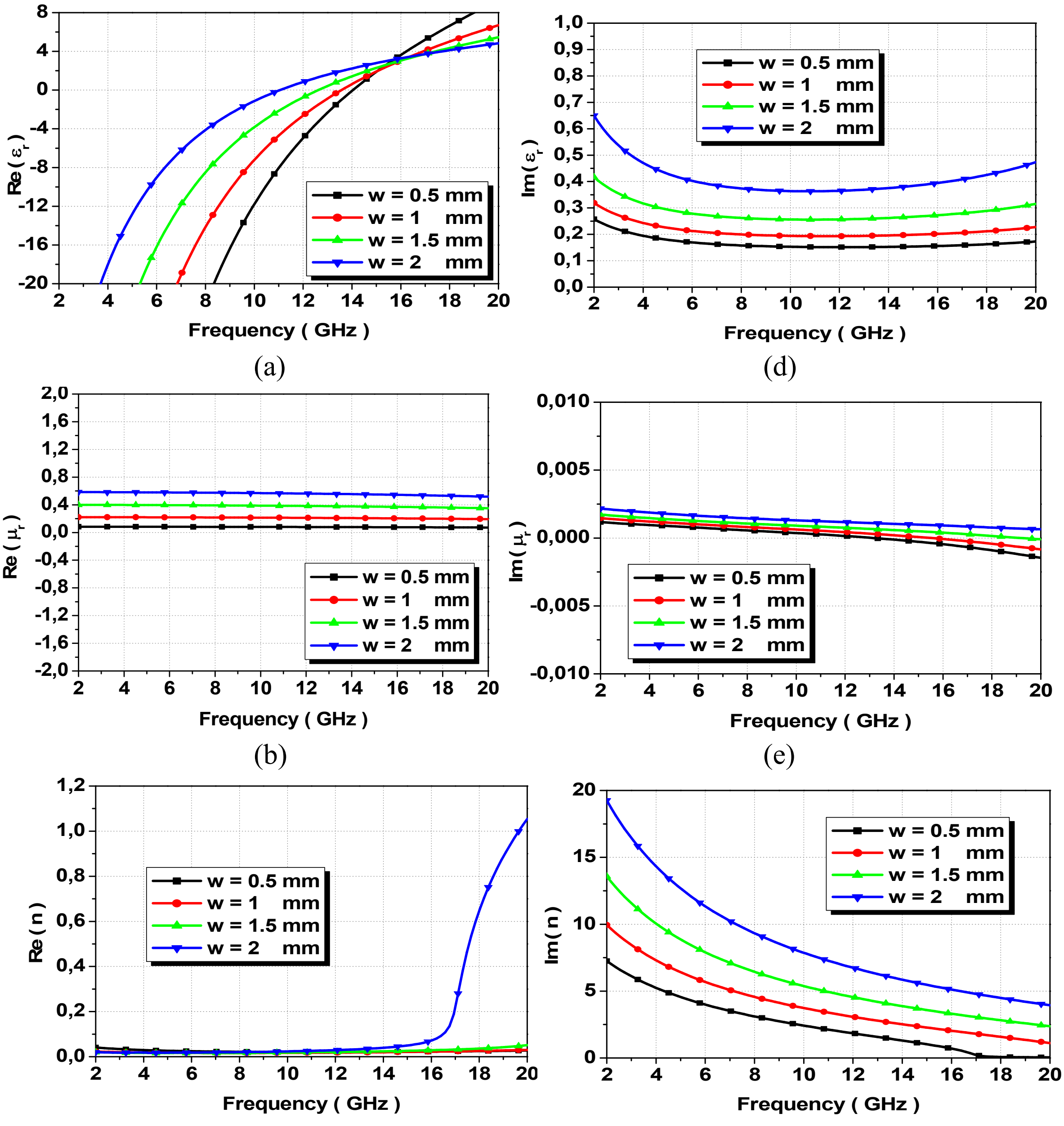
(b) (e)

(c) (f)

***Figure* 4.7**: Effect of the periodic length on the constitutive parameters of the unit cell (a), (b), and (c) respectively the real parts of the permittivity, permeability, the refractive index, and (d), (e), (f) are respectively the imaginary parts of the permittivity, permeability, the refractive index.

b. Effect of the cross width *w*

We plot the effective constitutive parameters of the metamaterial connected cross for different values of the width of metallization cross. This study allows us to choose the dimensions of the conductive, which permit to have a refractive index close to zero.



(a) (d)

(b) (e)

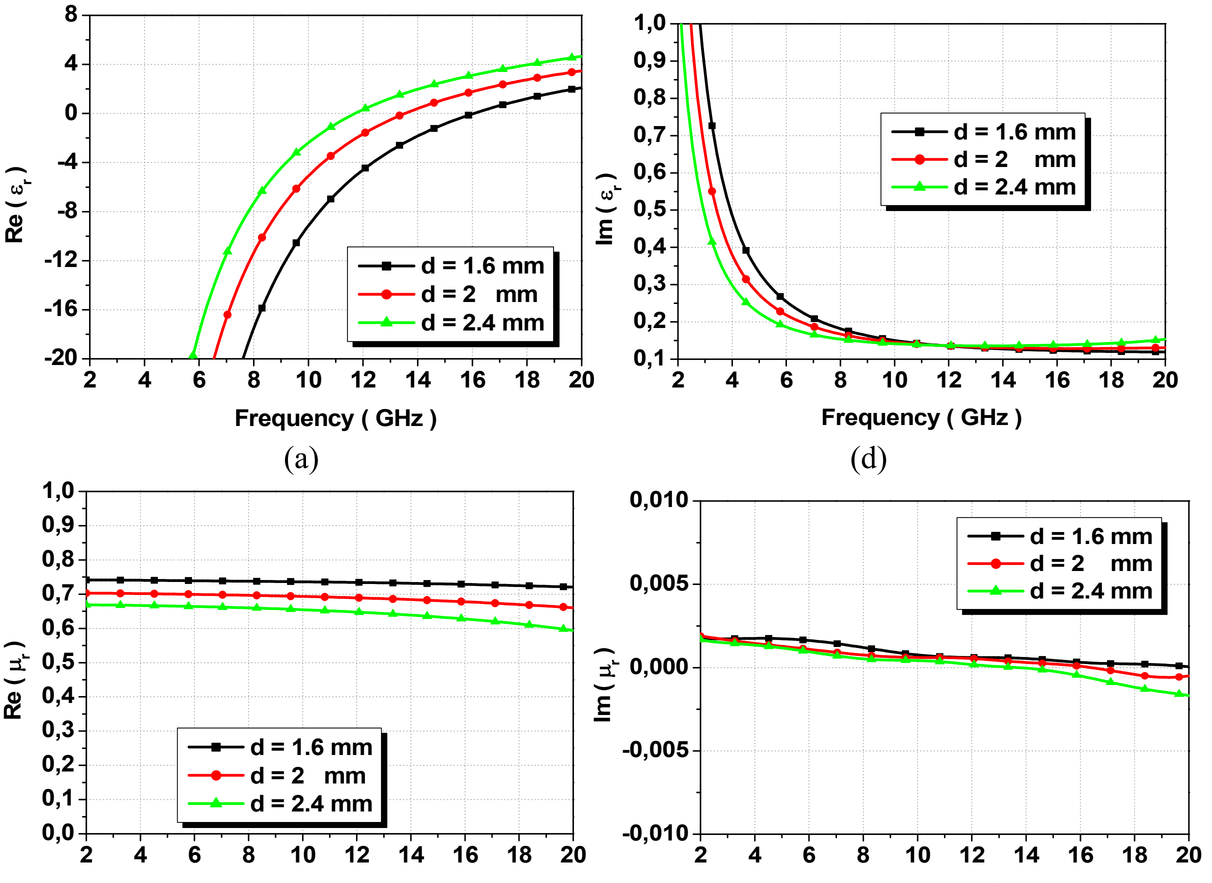
(c) (f)

***Figure* 4.** 8: Effect of W the metallization cross width**:** on the constitutive parameters of the unit cell (a), (b), and (c) respectively the real parts of the permittivity, permeability, the refractive index, and (d), (e), (f) are respectively the imaginary parts of the permittivity, permeability, the refractive index.

For the value of $w = 2\,mm$, below the plasma frequency, the real part of the refractive index is close to zero while the imaginary part is great.

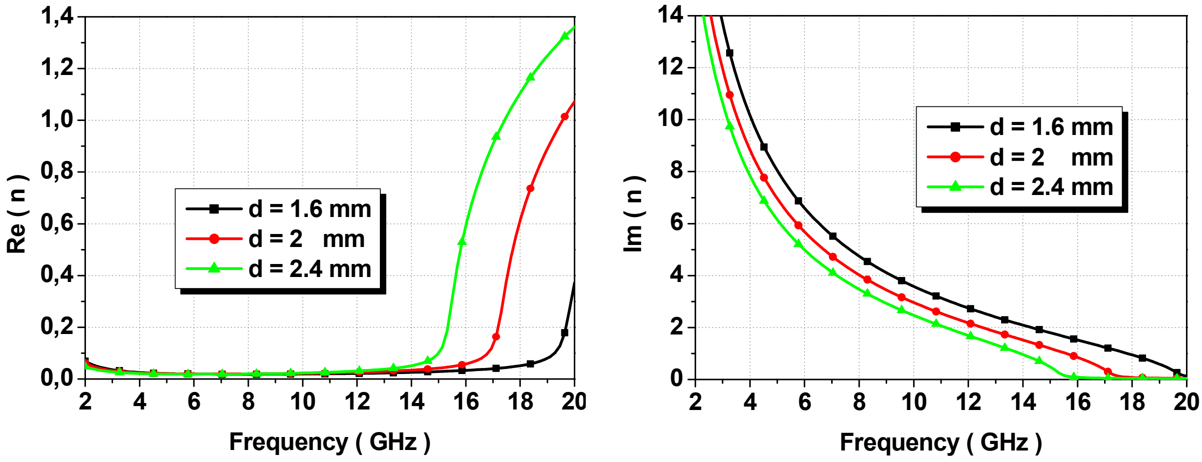
c. Effect of the dielectric thickness d

$\boldsymbol{Figure}$ **4.** 9 represents the various values of dielectric substrate thickness d, from these figures; we observe that increasing *d* allows the decreasing of the permittivity real part to close the zero.



(a) (d)

(b) (e)



(c) (f)

***Figure* 4.9**: Effect of d the substrate thickness on the constitutive parameters of the unit cell.

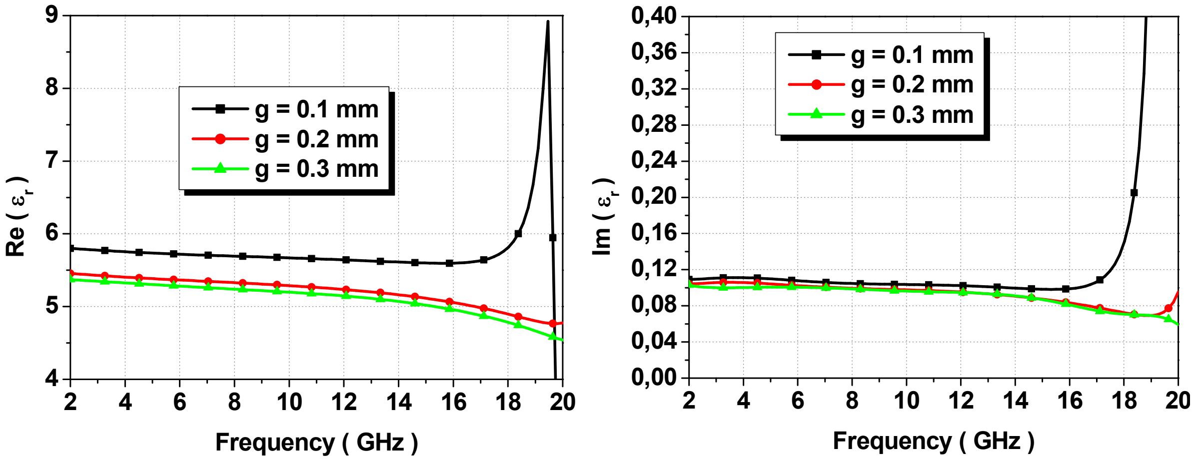
(a), (b), and (c) respectively the real parts of the permittivity, permeability, the refractive index, and (d), (e), (f) are respectively the imaginary parts of the permittivity, permeability, the refractive index

According to ***Figure* 4.9** we observe that the increasing of *d* shifts the plasma frequency to the lower frequencies and decreases losses in the metamaterial. Indeed, the imaginary parts of the metamaterial complex parameters (ε) , $Im(\mu)$ and $Re(n)$ are close to zero. We choose the largest value which is represented by *d = 2.4 mm.*

III. 2 Disconnected unit cell

a. Effect of the gap "g"

The disconnected cross type metamaterials unit cell has the same geometric and characteristics as the connected cross type unit cell. The disconnection is ensured by four gaps at the branches ends of the cross as shown in ***Figure* 4.6 − *c***. We examine the effect of the gap g on the three constitutive parameters of the disconnected cross type metamaterial.



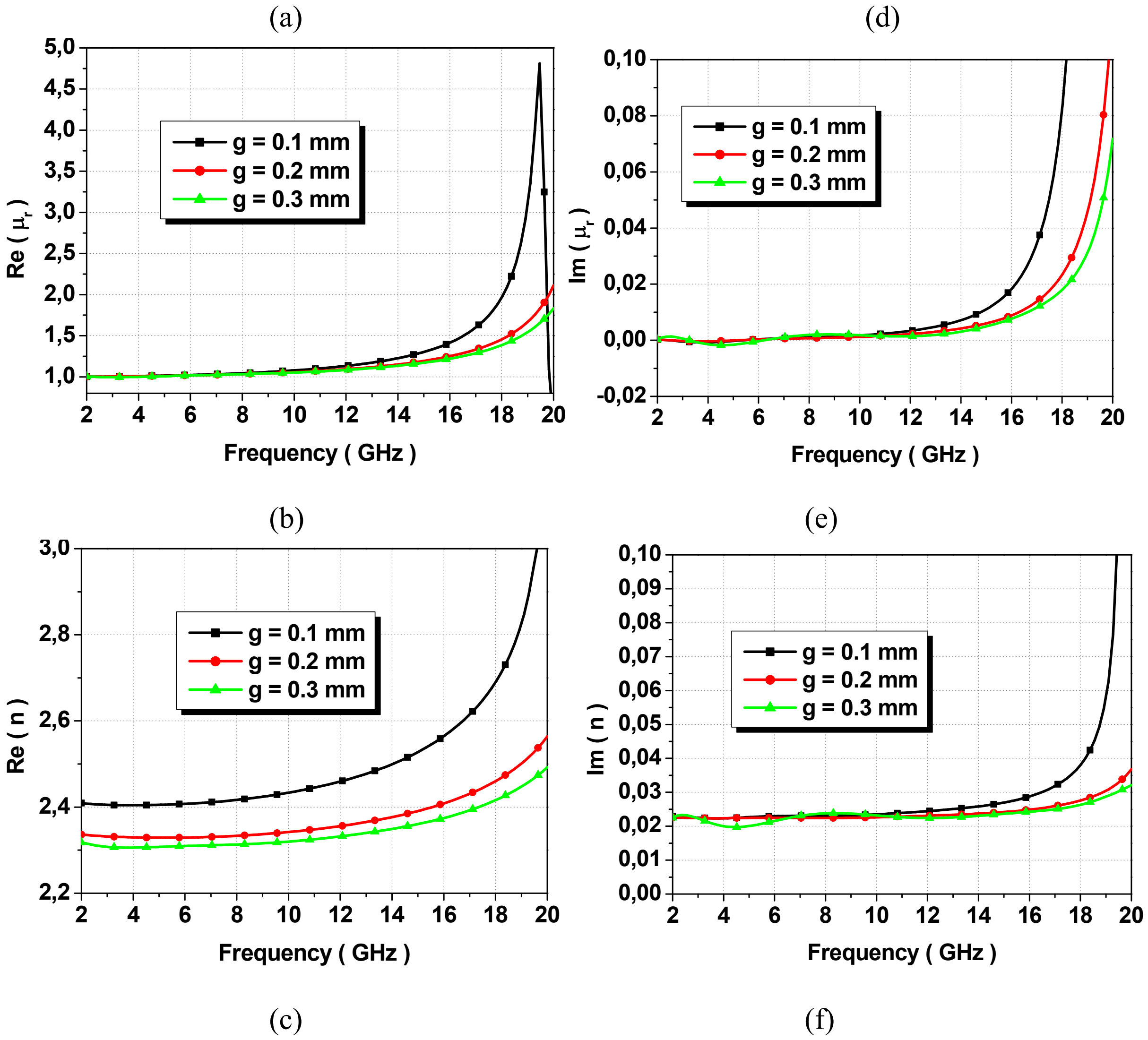


***Figure* 4.** 10: Effect of g the gap between two unit cells on the constitutive parameters of the unit cell.

(a), (b), and (c) respectively the real parts of the permittivity, permeability, the refractive index, and (d), (e), (f) are respectively the imaginary parts of the permittivity, permeability, the refractive index.

In this part we note that the imaginary resort always approaches zero, whereas the real part with respect to the reflection coefficient is greater than 2. So, for $g = 0.3\ mm$ we have a $Re\ (n) \approx 2.3$.

We can choose the metamaterial unit cell dimensions which give the desired behaviors of our agile metamaterial that are: $P = 3\ mm$, $d = 2.4\ mm$, $w = 2\ mm$, a substrate dielectric constant $\varepsilon_r = 4.4$ and a gap of $g = 0.3\ mm$.

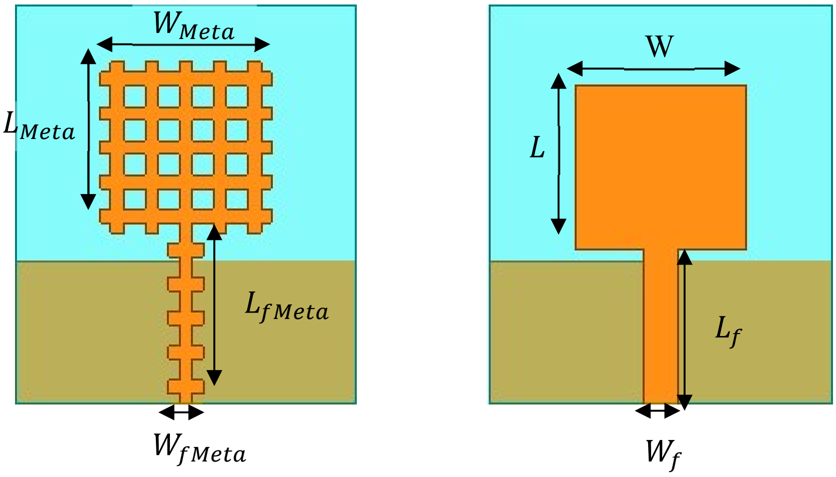
IV. Metamaterial microstrip antenna

In the previous section, we have seen the characteristics of the agile unit cell, which is used as a building block to realize a metamaterial agile microstrip antenna with wide-band and multi-band at the same time. We replaced the antenna metal part with a grid composed of the connected type unit cells. The grid dimensions are: W_{Meta} , and L_{Meta} for the patch and W_{fMeta} and L_{fMeta} for the feed line. The metamaterial antenna dimensions are the same with that of the conventional antenna, as shown in $\boldsymbol{Figure\ 4.}11$.

We will tack as reference antenna the enhanced metallic microstrip antenna depicted in $\boldsymbol{figure\ 4.4}$, and it will be mentioned as "conventional antenna".

The conventional antenna length and width are $L = W = 14{,}5\ mm$ so we chose $W_{Meta} = L_{Meta} = 15mm$ which correspond to 5 unit cells. The feed line is $L_f = 13{,}5$ mm so the metamaterial feed line leght is choose to be $= L_{fMeta} = 15$ mm which correspond to 5 unit cell seize. The feed line which is $W_f = 2{,}85\ mm$ which is smaller than one unit cell size so we are constraint to choose W_{fMeta} =3 mm one unit cell size.

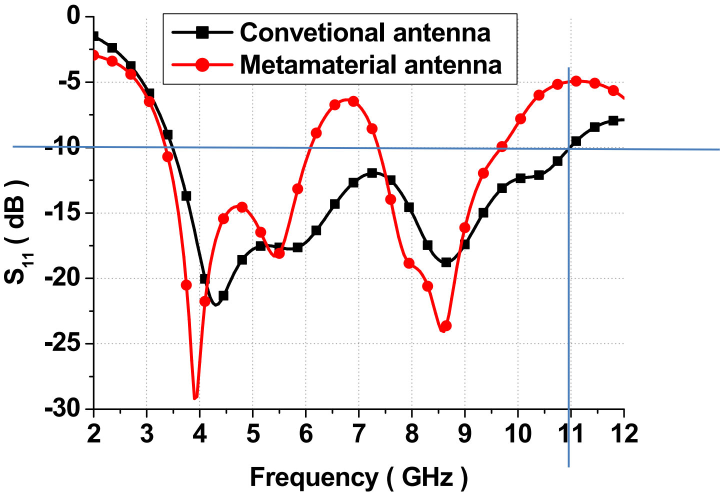
The dimensions of radius *R* of the notches are *R=3mm* which is equal to the size of one unit cell.



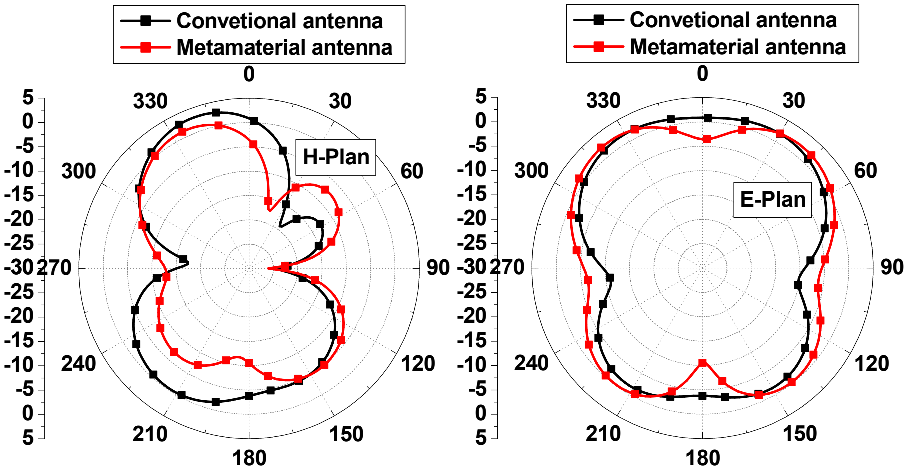
(a) (b)

$\boldsymbol{Figure\ 4.}11$: (a) Metamaterial patch antenna, (b) conventional patch antenna

$$W = W_{Meta} = L_{Meta} = L_{fMeta} = 15\ mm\ ,\ W_{fMeta} = 3mm\ ,\ L = 14{,}5\ \text{mm},\ L_f = 13{,}5\ mm,\ W_f = 2{,}85\text{mm}.$$



$\boldsymbol{Figure}$ **4.** 12: Reflection coefficient comparison between the conventional and metamaterial antennas



$\boldsymbol{Figure}$ **4.** 13: Radiation pattern comparison between the conventional and metamaterial antennas

$\boldsymbol{Figure}$ **4.14** shows the Reflection coefficient of the two antennas, the conventional metallic one and our metamaterial one, which represented in $\boldsymbol{Figure}$ **4.** 11 (a) and (b). We note that the conventional antenna presents an ultra-wide band at $-10\ dB$ frequency which varies from 3.5 Ghz to 11 GHz. However, the metamaterial antenna presents two wide-bands: The first band is of 2.65 GHz width (3.35 – 6 GHz) centered on 3.9 GHz, and the second one is of 2.3 GHz (7.3 $-$ 9.6 GHz) centered on 8.5 GHz. We have a good matching comparing to the conventional antenna reflection coefficient is around of $-29.18\ dB$ in the lower frequencies of $f\ =\ 3.9\ GHz$, at this frequency the metamaterial antenna presents a gain of 4.58 dB

We are going to use a cross-type unit cell, which can be controllable and has two different behaviors through an external control system represented by switches as we explained in sections III. The connected type behaves like a conducting material, by this type we make the feed line and the patch parts, for imitate the proposed metallic antenna in the previous part of this chapter in the section II.2.

In the metamaterial proposed antenna, the metallic part will be replaced with many crosses of connected type metamaterial; the disconnected type will replace the selected cutting parts. We just modify the state of switches at the level of the unit cell concentrated at the patch corner to the ON state like the ***Figure* 4.** 14 shows.

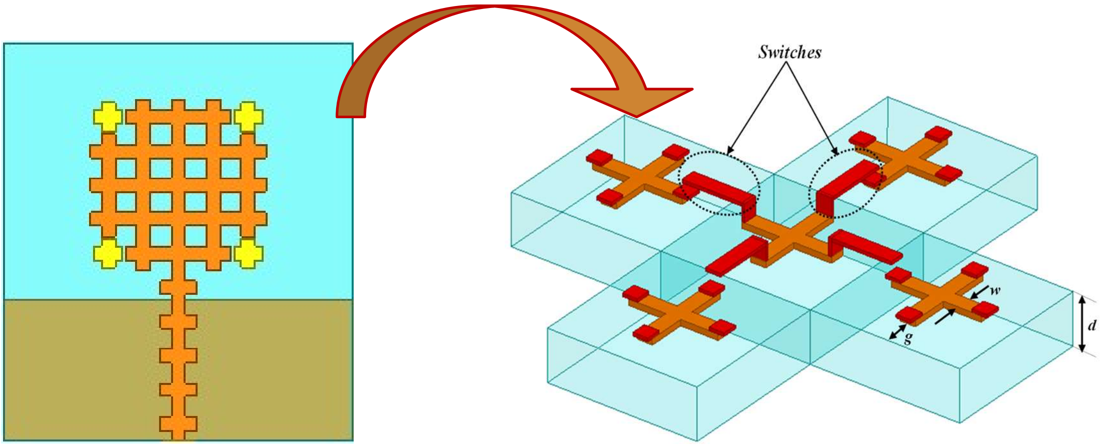


***Figure* 4.** 14 : Metamaterial proposed antenna

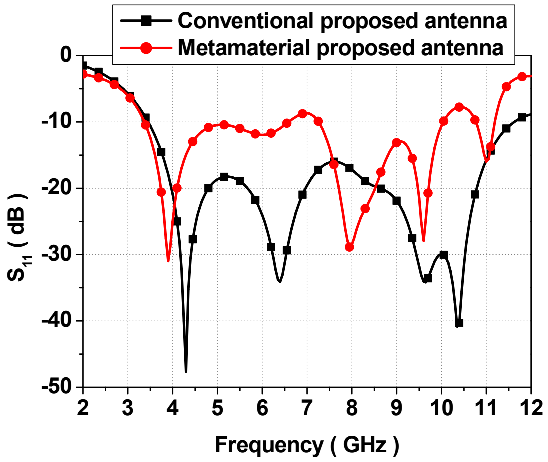


***Figure* 4.** 15: Conventional and metamaterial proposed antennas comparison

$\boldsymbol{Figure}\ \mathbf{4.16}$ indicates that the Metamaterial proposed antenna offers two wide-bandwidths:

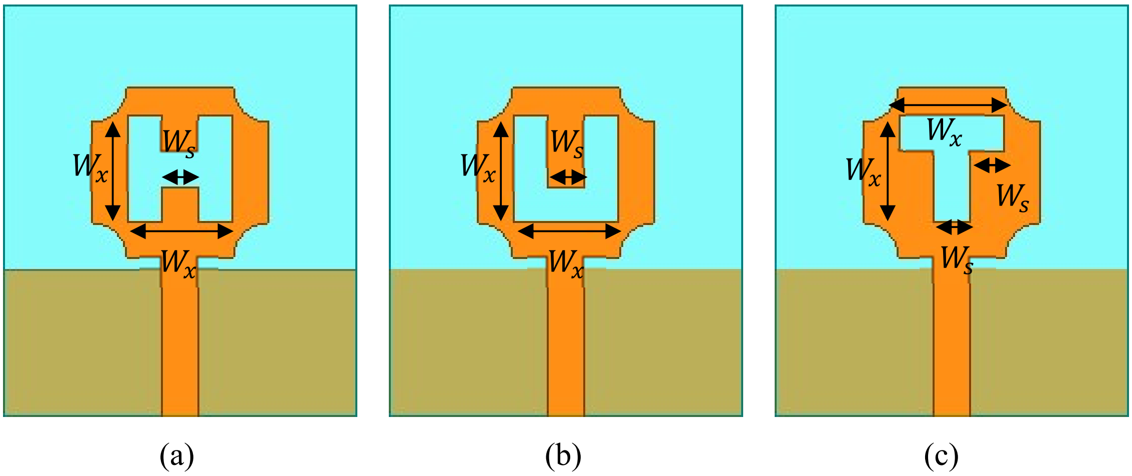
- The first bandwidth is of $3.3GHz$ that spans from $3.35\ to\ 6.65\ GHz$.
- The second one is of $2.7\ GHz$ that spans from $7.3\ to\ 10\ GHz$., The lower resonance frequency is of $-30.08\ dB$ at $3.9\ GHZ$.

The gain of this metamaterial antenna at $7.8\ Ghz$ is $4.85dB$.

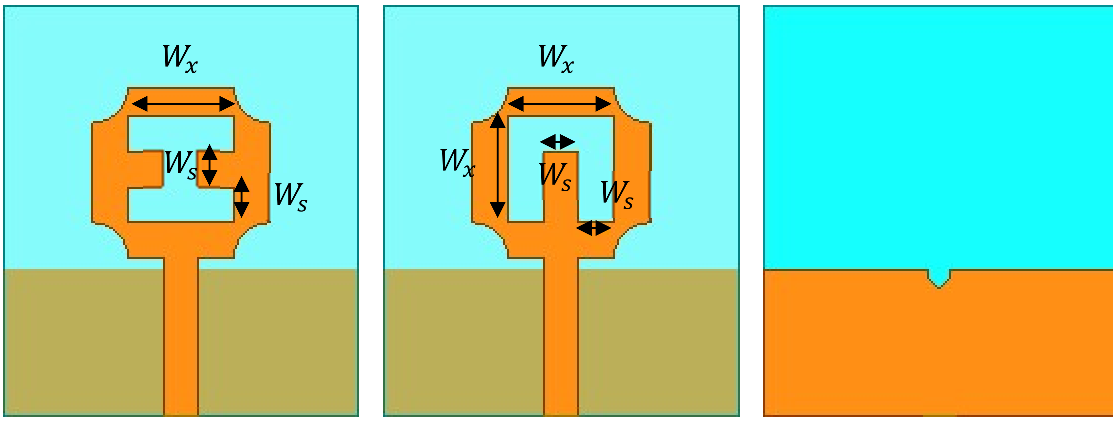
We note that the metamaterial antenna has globally the same behavior as the reference antenna, except that the adaptation is less good, which should be improved by other techniques such as adding slots in the patch.

IV. 1 Controlling the metamaterial antenna frequency operating bands

Etching slots on radiating element antenna disturbs the patch current distribution and consequently change the antenna impedance matching and the bandwidth. This later can pass from a broadband to a multiband antenna behavior. There are various slot shapes, which can be implemented in the patch as shown as in the $\boldsymbol{Figure}\ \mathbf{4}.17$ [67].



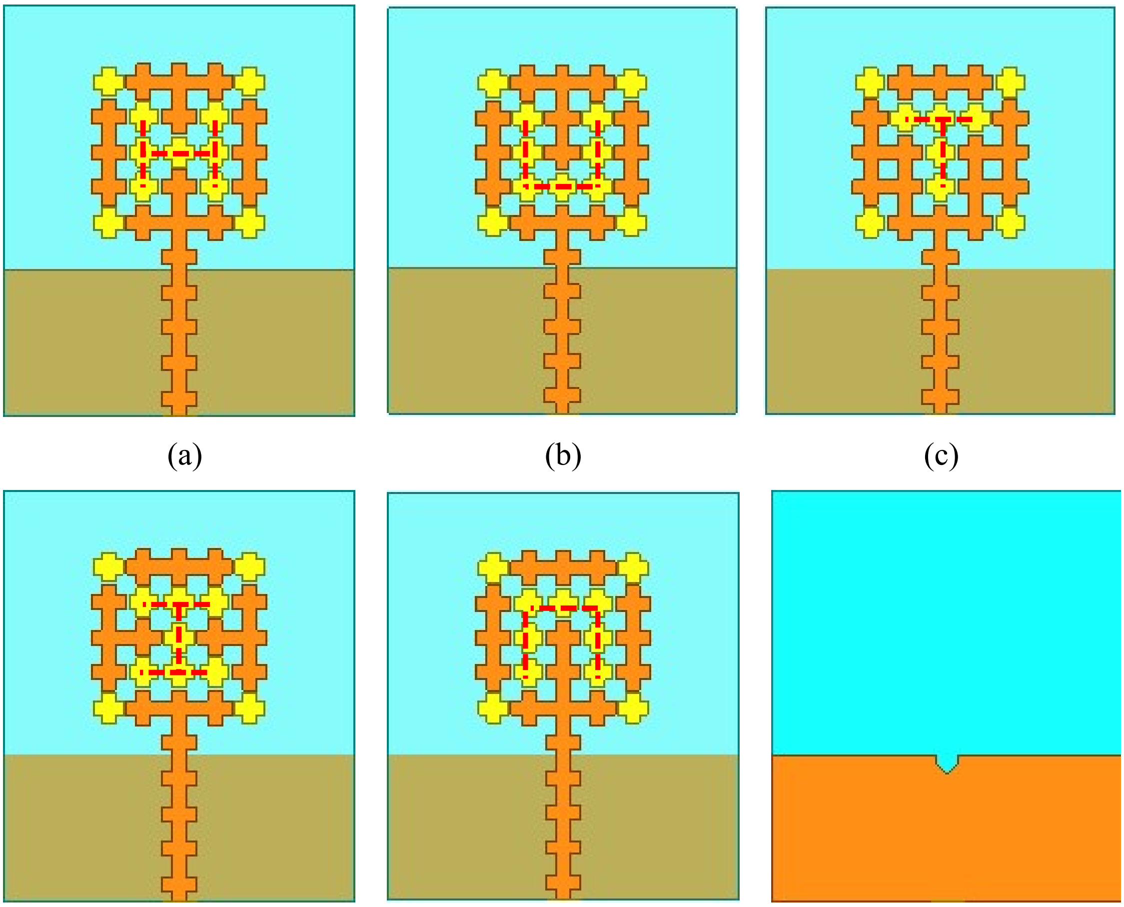
(a) (b) (c)



(d) (e) (f)

Figure 4.16: Conventional proposed antenna with different slots shape

(a) H-slot, (b) U-slot, (c) T-slot, (d) inversed H-slot, (e) and inversed U-slot, (f) back side if the five antennas with: $W_s = 3\ mm, W_x = 9\ mm$.

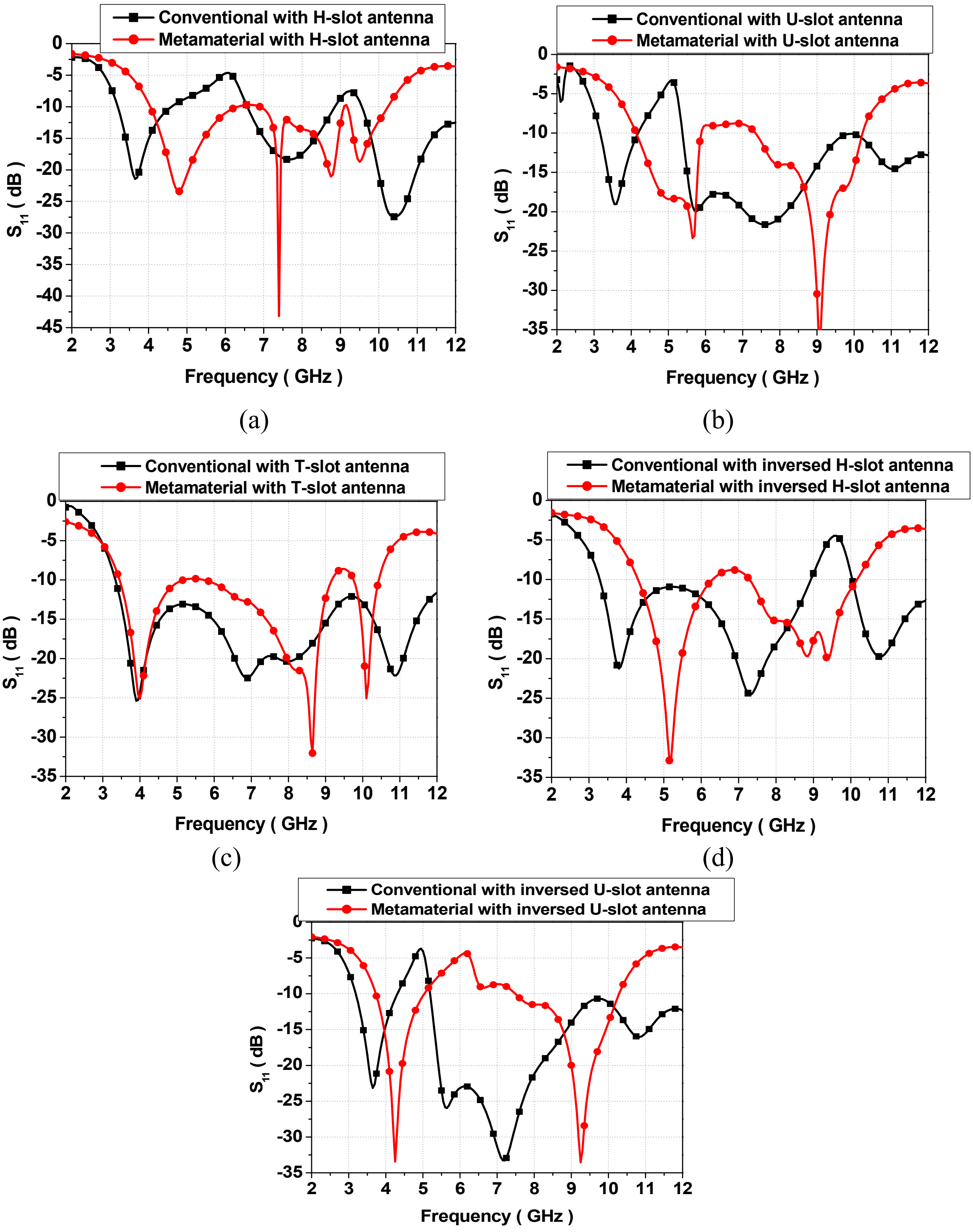


(a) (b) (c)

(d) (e) (f)

Figure 4.17: Metamaterial proposed antenna with different slots shape, (a) H-slot, (b) U-slot, (c) T-slot, (d) inversed H-slot, (e) and inversed U-slot, (f) back side if the five antennas.

It is worth mentioning that etching out slots in the patch of antenna introduces new bands and affects impedance matching due to the change of the current flow and distribution on the radiating patch. We propose to experiment five solt shapes etched on the antenna radiating element. As it can be seen in $\boldsymbol{figure}$ $\mathbf{4.15}$ and $\mathbf{4.16}$, the selected slot shapes are: The H slot, The inverted H slot, the T slot, the U slot and the Inverssed U slot.



(a) (b)

(c) (d)

$\boldsymbol{Figure}$ $\mathbf{4.18}$: The reflection coefficient comparison between conventional and metamaterial antenna for various shapes of slots (a) H-slot, (b) U-slot, (c) T-slot, (d) inversed H-slot, (e) and inversed U-slot.

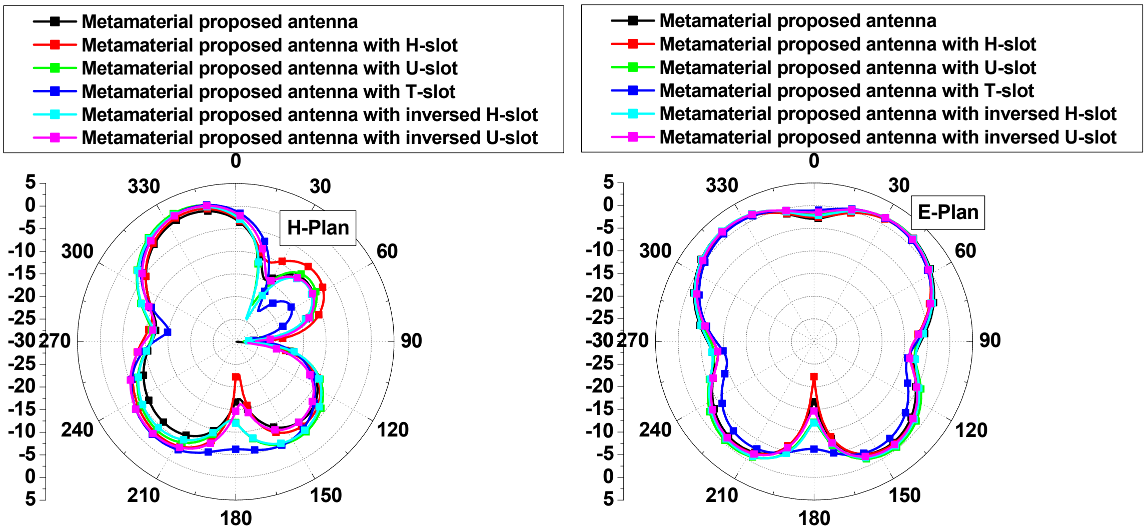


***Figure* 4.19:** Radiation pattern of metamaterial proposed antenna with different slots shape at $f = 7.8\ GHZ$.

***Figure* 4.19** shows the behavior of the metallic and metamaterial microstrip antennas with the selected slot shapes etched on the radiating element. The antennas with U , Inversed U and inversed H slot shapes have a behavior, which can be seen as bi-wide bands ,The H-slot antenna provides three wide-bands .While the antennas with a T present a behavior, which can be considered as ultra wide band.

It is worth mentioning, that using metamaterial to design the antenna allows us to control the antenna behavior by simply flip the behavior of some unit cells. Changing the behavior of some unit cells from a dielectric to conducting medium is equivalent to etch notches on the antenna and hence control its frequency response.

From ***figure* 4.20** one can see that adding notches on the radiating element does not affect considerably the antenna radiation pattern.

V. Conclusion

In this work, we present a new design of a Multi-wideband Microstrip patch antenna. This design allows us to satisfy ultra wide bandwidths covering different frequency ranges for WLAN and X-bands. This can be the first step to smart antennas which can present self-parameters control such as auto impedance matching, auto beam forming and auto frequency tuning.

General conclusion

This work presents a new technique to design a Multi-wideband Microstrip patch antenna which allows us to satisfy multi-wide bandwidths covering different frequency ranges for WLAN and X-bands. This can be the first step to smart antennas which can present self-parameters control such as auto impedance matching, auto beam forming and auto frequency tuning.

In the first chapter of this work we have seen a description of metamaterials, then, in the second one we have presented Microstrip patch antennas and their characteristics, the characteristics of ultra-wide, multi-band antennas and also the slot’s effect in microstrip patch antennas have been presented in the third chapter.

In the last one, we have seen the details of simulation which contain a description of the conventional and the proposed antennas, we described also the metamaterial unit cell, then we have studied the different slot’s effects on the antenna. we have also used metamaterial antennas with the same parameters and compared it with the metallic antennas.

The antennas with, U, inversed H and Inversed U slot shape have a behavior which can be seen as a bi-wide-bands. While the antennas with H slot shape presents a behavior, which can be considered as three-wide band.

It’s worth mentioning, that using metamaterials to design the antenna allows us to control the antenna behavior by simply flip the behavior of some unit cells. Changing the behavior of some unit cells from a dielectric to conducting medium is equivalent to etch notches on the antenna and hence control its frequency response. The high frequency structure simulator (HFSS) is used to design and simulate the antennas behaviour over the different frequency ranges and graphs are plotted using the software ORIGIN.

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