République Algérienne Démocratique et Populaire
Ministère de l'Enseignement Supérieur et de la Recherche Scientifique

Université Amar Thelidji- Laghouat

FACULTE: DE TECHNOLOGIE
DEPARTEMENT : D'ELECTRONIQUE

MEMOIRE DE MASTER

Réalisé par : Hadjira FERRADJI
Nour Elimen TAHRI
DOMAINE : Technologie
FILIERE : Télécommunications
OPTION : Systèmes de Télécommunications

Thème

Metamaterial antennas with defects

Jury de soutenance :

Nom et Prénom	Grade	Qualité
Mme Mokhtaria MESRI	Prof	Président
Mr Mohsen Saleh Chaker	Dr	Examinateur
Mr Mouloud BOUZOUAD	Prof	Encadreur

Promotion : 2020/2021

Acknowledgements

First and foremost, we thank God who helped us achieving this project. We would like to take the opportunity to thank sincerely anyone who contributed in any way, to the achievement of this work.

Our thanks to Professor Mouloud **BOUZOUAD,** our supervisor who has guided us, made suggestions, as well as for his constant encouragement. So, thank you very much for everything Sir.

Our heartfelt thanks also go to Miss, **Khadidja BOURAS** for documentation, support and advice lavished, throughout this work.

We do not forget Sir **Abdelhadi LABIAD** for helping us to provide a more systematic work.

Our thanks go to all our teachers during our long years of study.

May the members of the jury find here our expression of gratitude for having accepted to examine our work.

Dedication

I dedicate this modest work to:

My dear daddy, and my dear mom who have been by my side to support me and encourage me.

To my brothers.

to my sisters.

To my partner HADJIRRA FERREDJI.

To my friends.

To all the family.

TAHRI NOUR ELIMEN

ملخص

في هذه المذكرة نقترح تصميم هوائي قابل لإعادة التشكيل باستخدام الميطمواد (metamaterial). من أجل تحقيق خاصية " قابلية التشكيل" صممنا خلية ميطمواد مرنة لها حالتا تشغيل مختلفتان. خلية الميطمواد المرنة تتكون من سلك ناقل على شكل صليب مطبوع على ركيزة عازلة. نضع في نهايات السلك الناقل على شكل صليب قواطع للتحكم في اشتغال الخلية.

عندما تكون القواطع في الوضعية المغلقة نتحصل على خلية الميطمواد من نوع خلية صليب متصلة التي توافق تصرف المادة الخارقة كمادة ناقلة (حالة التشغيل الأولى لخلية الميطمواد) و في حالة ما تكون القواطع في الوضعية المفتوحة نتحصل على خلية الميطمادة من نوع خلية صليب منفصلة التي توافق تصرف الميطمادة كمادة عازلة (حالة التشغيل الثانية لخلية المادة).

في تصميمنا للهوائي القابل لإعادة التشكيل قمنا باستخدام الميطمواد من نوع الصليب المتصل عوض الأجزاء الناقلة و الميطمادة من نوع الصليب المنفصل عوض الأجزاء العازلة المستعملة في الهوائي الأصلي الذى أخترناه كمرجع.

الهوائي المرجع اخترناه من قاعدة المنشورات لتوفير معطيات تجريبية لمقارنتها بنتائج المحاكاة التي تحصلنا عليها. هذا الاختيار يسمح لنا من التحقق من صلاحية نموذجنا. الهوائي المرجعي المختار مصمم لتطبيقات ISM/Wearable هو عبارة عن لوحة ناقلة مستطيلة الشكل مزود بثغرات ذات قياسات محددة لتحقيق تشغيل ثنائي النطاق. نتائج المحاكاة المتحصل عليها تصادقها النتائج التجريبية للهوائي المرجعي. ستسمح لنا هذه الدراسة بالتقدم في بحثنا خطوة إلى الأمام في تحقيق هوائي ذكي أو مرن على أقل تقدير.

Abstract

In this dissertation, we propose a design of a reconfigurable metamaterial antenna. For this purpose, in order to ensure the reconfigurability, we design an agile metamaterial unit cell which has two different operating states. The agile metamaterial unit cell consists of a cross type conductor printed on a dielectric substrate. Each branch of the conductor cross is ended by a switch. If the switches are in ON state, we obtain a connected cross type unit cell which operates in the state one (ON state), otherwise (switches in Off state) we obtain a disconnected cross type unit cell which operates in the second operating state (Off Stat). In ON state, the obtained metamaterial behaves as a conductor while in Off state the metamaterial behaves as an insulator. In our reconfigurable antenna design we use the connected and disconnected cross type metamaterial to replace conducting surfaces and non-conducting surfaces, respectively, of a conventional antenna used as a reference. The reference is chosen from the literature to compare its experimental results to our simulation. This has enabled us to validate our design prototype. As a reference antenna, we use that proposed in ‘a planar dual band antenna for ISM/wearable applications’. This antenna is designed for ISM/ Wearable applications. It consists on a rectangular patch loaded with several slots with specific dimensions to achieve a dual-band propriety in ‘a planar dual band antenna for ISM/wearable applications. The simulation results agree well with experimental measurements of the reference antenna. This study will allow us to advance in our research and make a step forward in the realization phase of a smart antenna otherwise at least an agile one.

Résumé

Dans ce mémoire, nous proposons la conception d’une antenne métamatériau reconfigurable. Pour atteindre ces objectifs, nous avons conçu une cellule métamatériau agile possédant deux états de fonctionnement différents. La cellule métamatériau agile consiste en un conducteur en forme de croix imprimé sur un substrat diélectrique. Chaque branche de la croix est terminée par un interrupteur. Si les interrupteurs sont à l’état fermé nous obtenons une cellule métamatériau de type croix connectée, correspondant au premier état de fonctionnement (Etat On). Dans le cas contraire, (interrupteurs à l’état fermée) nous obtenons une cellule métamatériau de type croix déconnectée, correspondant au deuxième état d fonctionnement (Etat Off). Dans le premier état de fonctionnement de la cellule métamatériau agile, le métamatériau obtenu se comporte comme un milieu conducteur, alors que dans le second état, il se comporte comme un milieu diélectrique. Dans notre conception de l’antenne métamatériau reconfigurable, nous utilisons le métamatériau du type croix connecté et déconnectée, pour remplacer les surfaces conductrices et non conductrices, respectivement, d’une antenne conventionnelle utilisé comme référence. L’antenne de référence est choisie dans la littérature pour comparer nos résultats de simulations à ces données expérimentaux. Ce choix nous permis de valider notre prototype. Comme antenne de référence, nous utilisons celle proposé dans la référence ‘a planar dual band antenna for ISM/wearable applications’. Cette antenne est conçue pour des application ISM/Wearable. Elle consiste en un patch rectangulaire chargé par plusieurs slots de dimensions spécifique pour assurer un comportement bi-bandes. Nos résultats de simulation sont en bon accord avec ceux expérimentaux de l’antenne de référence. Cette étude nous permettra d'avancer dans nos recherches et de faire un pas en avant dans la réalisation d'une antenne intelligente sinon au moins agile.

CONTENTS

Chapter II: State of art

Chapter III: Metamaterial based wearable antennas

CONTENTS

Chapter IV: Reconfigurable Metamaterial antenna with defects

List of Figures and Tables

List of Figures and Tables

List of Figures and Tables

List of Tables

Chapter I : Intoduction

I. Introduction

Although passing long time from formulating Maxwell’s equations, the subject of electric and magnetism did not remain stagnant during that time. Since the full understanding of the electric and magnetic fields inside matter can only happen after studying the atomic nature of matter, in other words, studying the behavior of materials when electromagnetic waves pass through them. The apparition of metamaterial has attracted more and more attention to this subject, where this new material can artificially show several new electromagnetic properties (i.e. negative refraction, perfect lensing, cloaking). One of the most important applications of metamaterials is antenna design. Due to the unusual properties of MTMs, antennas can be designed with novel characteristics which cannot be realized with traditional materials.

Many designs have been studied and reported to improve antenna properties, and we will take as an example the proposed antenna in [1] where they design a metallic antenna for ISM/ Wearable applications, where the patch part is loaded with several slots to obtain a dual band antenna.

In our work we'll try to simulate the same antenna with the same dimensions for the same purpose, but in a slightly different method, where we'll replace the structure made of the conventional material with a structure made of our agile metamaterial to obtain a reconfigurable antenna. This antenna is chosen to be used as a reference and to compare its experimental results to our simulation ones. This choice enables us to validate our design prototype and will also bring improvements to the work that has been conducted last year, by our partners during their Master dissertation [2]. Our agile metamaterial unit cell has two different operating states. It consists on a cross type conductor printed on a dielectric substrate. Each branch of the conductor cross is ended by a switch. If the switches are ins the ON state, we obtain a connected cross type unit cell which operates in the state one (ON state), otherwise, (switches in Off state) where we obtain a disconnected cross type unit cell which operates in the second operating stat (Off State). In the first case, the unit cell, the obtained metamaterial behaves as a conductor while in the second state, the metamaterial behave as an insulator.

In our reconfigurable metamaterial antenna, we replace conducting and non-conducting areas of the original conventional antenna, by connected and disconnected cross type metamaterial, respectively. The behavior of the unit cell (by flipping between the two cross type unit cells -connected and disconnected type-) is controlled by integrating an external switching system such as PIN diode between two adjacent unit cells. Based on these two types, we'll simulate the agile metamaterial antenna which emulate the metallic one where we replace the patch part with connected cells, and replace the loaded slots (defects) in the patch with disconnected cells.

The first chapter serves as an introduction to metamaterials, by displaying a review of some of the important ideas found in the literature for this research field.

In the second chapter, we provide an overview of reconfigurable antennas and how they can be applied in metamaterials-based wearable antennas.

For the third chapter, we re-simulated a dual-band planar antenna for ISM/wearable applications [1], in order to compare our results with their experimental results, based on those results, we simulated the antenna using metamaterials, which is carried out using the simulation software HFSS (High-Frequency Structure Simulator).

Each simulation requires a time of 20/24 hours. Therefore, a number of challenges had to be raised in the lab throughout the simulation (power outages, pressure on the simulation apparatus, etc), so only the important experiments have been performed.

Chapter II: State of art

Chapter II : State of art

II.1 Introduction

The electromagnetic properties of a homogeneous material in nature are determined by its molecular composition. The macroscopic electric and magnetic fields of a wave propagating in a material are defined as the averages of microscopic fields of the wave. The behavior of materials toward electromagnetic waves is described by the electric permittivity (ε) and magnetic permeability (μ) parameters [3]. Another important material parameter can be defined, the refractive index $n=\sqrt{(\varepsilon \mu)}$, as usually both electric permittivity and magnetic permeability are positive, the refractive index will be also positive.

Metamaterials are artificial materials, whose sub-units are of a larger scale than molecular and with unusual electromagnetic properties that are not found in naturally occurring materials (such as having a negative permittivity and permeability, and a negative refractive index).

This artificial materials opens the door to realize all possible material properties by designing different cellular architectures and using different substrate materials. As for the importance and utility of metamaerials, they have found and finding a lot of applications or potential applications [4].

II.2 Brief history

The earliest attempts to synthesize electromagnetic properties artificially go back well over a century to the pioneering work of Bose in 1898 and Lindman in 1914 , who explored what today might be called artificial chiral structures in the millimeter-wave and microwave regions, respectively. However, the consolidated pursuit of synthesizing useful electromagnetic properties artificially was established in the seminal study of the so-called “artificial dielectrics” in the 1940s, 1950s, and 1960s [5].

The Metamaterial was firstly known as left-handed material (LHM) or negative refractive index material (NIM), the first theoretical work was proposed by Veselago theoretically in 1968, who examined solutions to Maxwell’s equations in hypothetical media exhibiting simultaneously negative isotropic permittivity and permeability. Research in LHM was stagnant for more than 30 years due to the lack of experimental verification. The first revolution dealing with LHM occurred in 1996 when Sir Pendry discovered the wire medium (array of copper wires with a specific radius and spacing) whose permittivity is negative, followed by the discovery of the split-ring resonator (SRR) would have a frequency band where μ is negative, also by Sir Pendry et al. in 1999 . The first artificial LHM was made by Smith et al.

in 2001 using the combination of wires and SRRs, In this famous experiment, the negative refraction phenomenon was verified.

The second revolution in metamaterials came in 2005 when the gradient refraction index medium was realized to bend electromagnetic waves, which was discovered by Smith et al. In 2006 the optical transformation was proposed to make invisible cloaks to control the propagation of electromagnetic waves using MTMs was discovered by Pendry et al. [4].

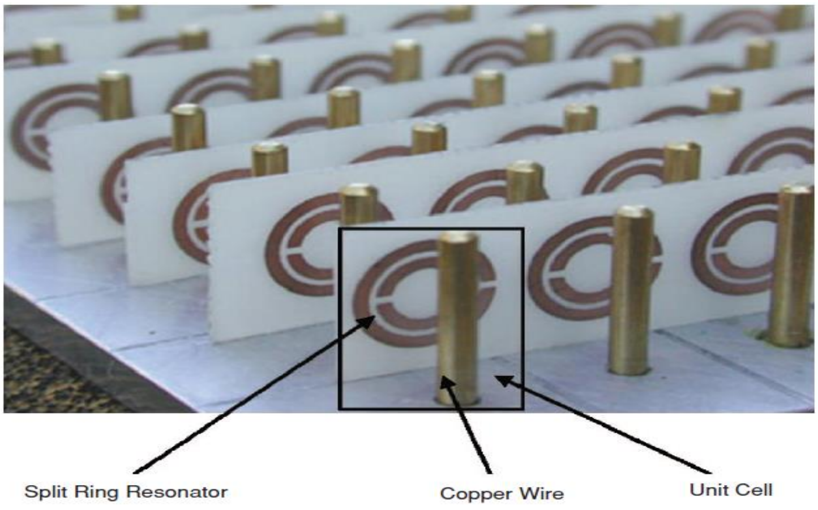


Fig. II.1 First left-handed test structure array made (SRRs/Wires Combination) by the San Diego group (courtesy D R Smith).

II.3 Definition of Metamaterial

There have been a large number of definitions for metmaterials, they can be generally defined as a class ‘artificial’ media, exhibiting extraordinary electromagnetic properties that cannot be found in natural ones [6].

Historically, the term of metamaterial was synthesized by Rodger M. Walser, University of Texas at Austin, in 1999, which was originally defined as “Macroscopic composites having a synthetic, three-dimensional, periodic cellular architecture designed to produce an optimized combination, not available in nature, of two or more responses to specific excitation” [4]. The name given to this structurally altered materials is based on the Greek (meta) that means “beyond” [6].

Actually, **a metamaterial is a macroscopic composite of periodic or non-periodic structure, whose function is due to both the cellular architecture and the chemical**

composition. If the metamaterial is regarded as an effective medium, there is an additional requirement that the cellular size is smaller than or equal to the sub-wavelength [4].

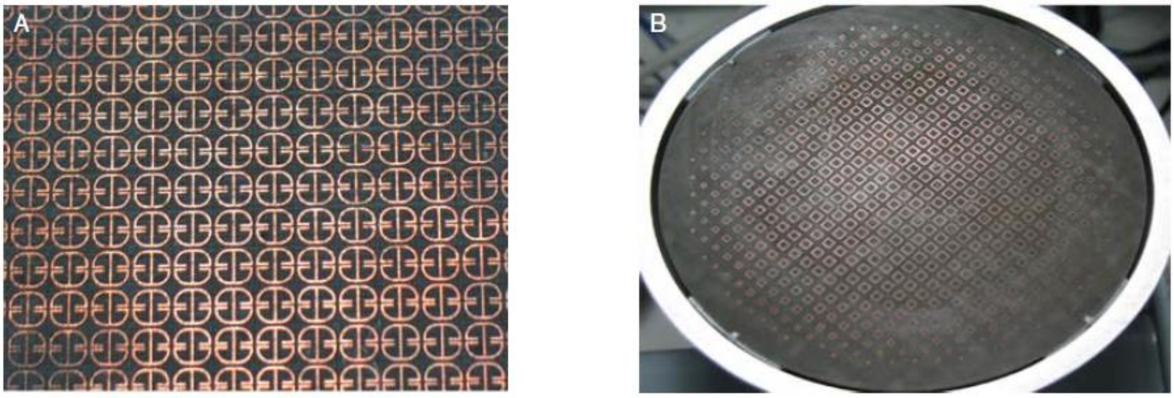


Fig. II.2 Two typical metamaterial structures in the microwave regime. (**a**) A periodic structure, which is equivalent to a homogeneous medium. (**b**) A non-periodic structure, which is equivalent to an inhomogeneous (gradient) medium.

II.4 Metamaterials classification

As mentioned before, the material properties are characterized by their electric permittivity ε and magnetic permeability μ which are related to the refractive index n=√(ε μ) On this basis, the materials can be classified as shown in Fig. I.4.

Figure I.4 illustrates all possible properties of isotropic and lossless materials in the ε−μ domain. In Fig. I.4, the first quadrant (ε < 0 and μ > 0) represents right-handed materials

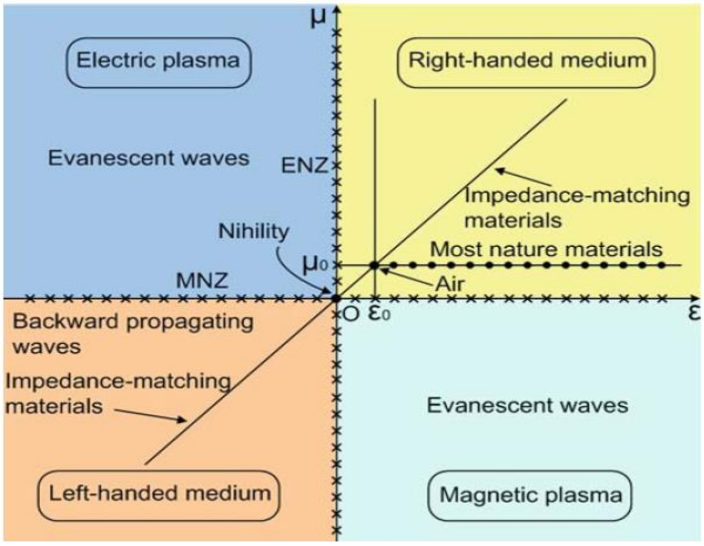


Fig. II.3 All possible properties of isotropic materials in the ε−μ domain.

(RHM), which support the forward propagating waves. From the Maxwell's equations, the electric field **E**, the magnetic field **H**, and the wave vector **k** form a right handed system. The second quadrant ($\varepsilon < 0$ and $\mu > 0$) denotes electric plasma, which support evanescent waves. The third quadrant ($\varepsilon < 0$ and $\mu < 0$) is the well-known left-handed materials (LHM), which was proposed by Veselago in 1968, supporting the backward propagating waves. In LHM, the electric field **E**, the magnetic field **H**, and the wave vector **k** form a left-handed system. The fourth quadrant ($\varepsilon > 0$ and $\mu < 0$) represents magnetic plasma, which supports evanescent waves.

In the ε–μ domain, there are several special lines and points indicating special material properties. For example, the point $\mu = -\mu_0$ and $\varepsilon = -\varepsilon_0$ and represents an anti-air in the LHM region, which will produce a perfect lens; the point $\mu = 0$ and $\varepsilon = 0$ represents a nihility, which can yield a perfect tunneling effect, the line $\mu = \varepsilon$ in both RHM and LHM regions represents impedance-matching materials, which have perfect impedance matching with air, resulting no reflections. Also, the vicinity of $\mu = 0$ is called as μ-near zero (MNZ) material, and the vicinity of $\varepsilon = 0$ is called as ε-near zero (ENZ) material, which has special properties [4].

II.5 Metamaterials Design [8]

In the past years, many design of metamaterials structures are introduced, such as thin wires, Swiss rolls, SRRs, electric SRRs (eSRRs), pairs of rods, pair of crosses, fishnets ,etc. Some of them display negative refractive index while, some of them are designed for either a specific magnetic or electric response. The basic structures of SRRs and thin wires are sufficient to achieve the required electromagnetic properties at frequencies below infrared.

II.5.1 Lattice of thin wires

The electric plasma frequency, w_{eq} , which can be defined as :

$$w_{eq}^2 = \frac{ne^2}{\varepsilon_0 m_{eff}} \qquad (1)$$

n = electron density ; **e** = electron charge.

ε_0 = vaccum permittivity ; **m_{eff}** = electron effective mass.

Typically, the electric response of natural conductive materials appears at high frequencies, (i.e. visible or UV band). The plasma frequency can be shifted to lower frequency range e.g. microwave region. the equation (1) shows that the shifting in plasma frequency can be achieved by reducing the electron density and electron mass.

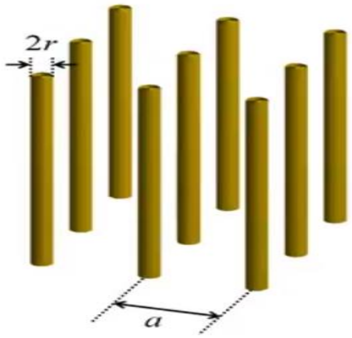


Fig. II.4 Lattice of thin metallic

Lattice of thin wires, a structure consists of thin parallel conducting wires. When excitation electric field is parallel to the axis of the wire so as to induce a current along them and generate equivalent electric dipole moment. From the analysis, given that “ a ” is the lattice spacing and “ r ” is the wire radius, the plasma frequency of the structure now becomes :

$$w_{eq}^{2} = \frac{2\pi c^{2}}{a^{2}\ln\frac{a}{r}}$$

The structure can be characterised by an effective permittivity that takes on a Drudes model, by assuming infinite length wire.

$$\varepsilon_{eff(w)} = 1 - \frac{w_{eq}^{2}}{w^{2} + j\Gamma w}$$

Where is responsible for the propagation loss. At $w < w_{ep}$ the permittivity becomes negative.

II.5.2 SRRs

A unit cell of the original double SRRs is basically composed of two concentric metallic rings with opposite splits or gaps. A current flow is established by the rings, which further builds a magnetic dipole parallel or anti parallel to the magnetic to the magnetic fields when the SRR is coupled to a magnetic field component oscillating in the axial direction. The loop inductance and gap capacitance are equivalent to an LC resonant circuit, causing a strong magnetic response at its resonance. The resonance frequency is lowered since the inner concentric ring contributes to the net capacitance of the double SRR. The ratio between the operating wavelength and lattice constant is hence boosted up by the ring, making the SRRs appear more homogenous to the electromagnetic excitations. Inspite of this, the inner ring can be removed without a significant impact on the SRRs function while shifting the resonance frequency. Lorentzian model describes a metamaterial structure composed of periodically aligned SRRs under a magnetic excitation by an effective magnetic permeability

$$\mu_{eff(w)} = 1 - \frac{Fw^2}{w^2 - w^2 m_0 + 2\Gamma w}$$

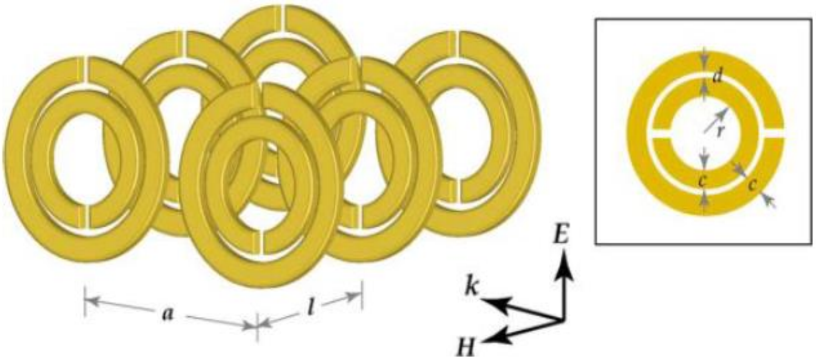


Fig. II.5 Double SRRs.

Where w_{mo} is the magnetic resonance frequency, Γ represents the energy dissipation, and F is the fill factor of the SRR. The magnetic resonance frequency and the SRRs geometry are related with each other through.

$$w_{m0}^2 = \frac{3Ic_0^2}{\pi In\frac{2c}{d}r^3}$$

The magnetic plasma frequency is the frequency where the permeability crosses zero and is given by :

$$w_{mp}^2 = \frac{w^2 m_0}{1 - F}$$

The SRRS have a positive response to the magnetic fields at frequencies lower than resonance and the response becomes negative between the resonance and plasma frequency. This structure supports paramagnetism ($\mu_{eff} > 1$) and diamagnetism ($\mu_{eff} < 1$), including a negative permeability.

II.5.3 SRRs/Wires Combination

The 1st DNG metamaterial was actually a combination of the thin wires based ENG structure and the SRR based MNG structure. It was assumed that the new composite material exhibited a macroscopic permittivity equal to that of the thin wire ENG medium and a macroscopic permeability equal to the permeability of the SRR based MNG medium. In the Fig. I.7 is shown such a combination of SRR and wires.

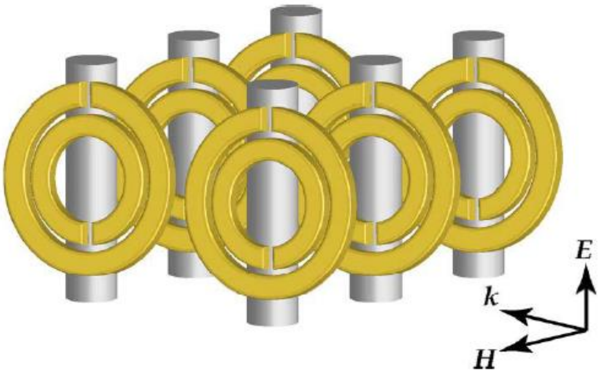


Fig. II.6 SRRs/Wires Combination.

II.6 Metamaterials properties

The electromagnetic properties of a homogeneous material in nature are determined by its molecular composition. The macroscopic electric and magnetic fields of a wave propagating in a material are recognized to be the averages of their microscopic fields.

Therefore, the electromagnetic behaviour of materials in nature is described by the electric permittivity (ε) and magnetic permeability (μ) parameters.

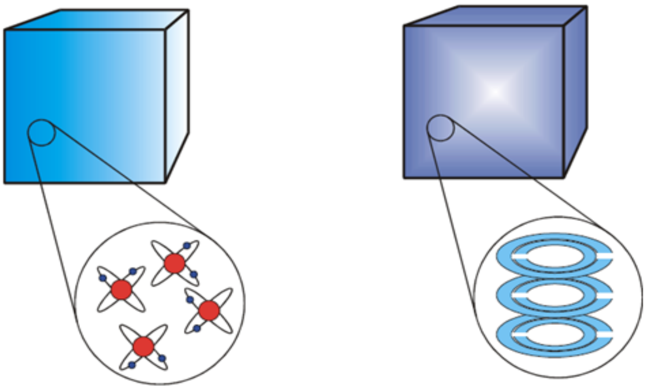


Fig II.7 Materiasl in nature are composed form molecules (left figure). Metamaterials are artificial media with specifically designed sub-units of several orders of magnitude higher than molecules.

The macroscopic behaviour of MTMs is governed by the geometry of subunits, which are usually composed from conducting materials. By specifically designing the sub-unit geometry, the macroscopic fields can be governed and therefore artificial media with novel electromagnetic properties can be manufactured, giving access to a new range of phenomena, such as negative refraction, perfect lensing and electromagnetic cloaking.

II.6.1 Negative Refraction

Veselago in 1968 realized that when a medium has both $Re(\varepsilon)$ and $Re(\mu)$ simultaneously negative, the real part of the refractive index is negative. Let us consider the refractive index formula: $n = \sqrt{\varepsilon\mu}$ which arises from Maxwell's equations. When the real parts of both $\varepsilon(\omega)$ and $\mu(\omega)$ are positive, the positive square root is chosen. For frequencies where $Re(\varepsilon) \to 0$, $\sqrt{\varepsilon}$ has a branch point. A solution can be found considering that causality force us to take a trajectory above the branch point, giving a positive imaginary solution for $\sqrt{\varepsilon(\omega)}$ when $Re(\varepsilon) < 0$. Similarly for $Re(\mu) \to 0$, $\sqrt{\mu(\omega)}$, takes a positive imaginary solution. Therefore,

$$n = \begin{cases} +\sqrt{\varepsilon(\omega)\,\mu(\omega)} & for \quad Re(\varepsilon) > 0\; and, or\; Re(\mu) > 0 \\ -\sqrt{\varepsilon(\omega)\,\mu(\omega)} & for \quad Re(\varepsilon) < 0\; and\; Re(\mu) < 0 \end{cases}$$

Waves propagating in a negatively refracting medium show unconventional behaviour. Consider Maxwell's equations:

$$\nabla \times E = \; i\omega\mu\mu_0 H \;\Rightarrow k \times E = \; \omega\mu\mu_0 H$$

$$\nabla \times H = -i\omega\mu\mu_0 E \;\Rightarrow k \times H = \; -\omega\mu\mu_0 E$$

Where E and H are the electric and magnetic fields of the form exp $(ikr - i\omega t)$ (where $r = xx + y\hat{y} + z\hat{z}$). It is easy to see that when both $Re(\mu)$ and $Re(\varepsilon)$ are negative, then the three

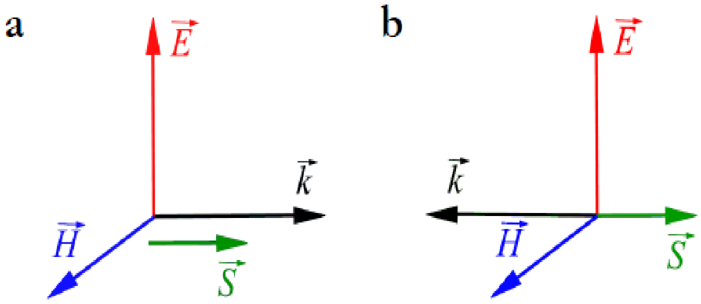


Fig. II.8 The triplets (a) of right-handed set of vectors and (b) of left-handed set of vectors with direction of the pointing vector S.

vectors k, E and H obey a left-handed rule. Also note that in this case, the wave vector k and the Poynting vector (S = E x H) are anti-parallel. This basically means that the wave (i.e. wave velocity) and the energy of the wave travel in opposite directions. Furthermore, negative refracting media show severa interesting properties, which were predicted by Veselago in 1968, such as a reversed Doppler shift and an obtuse angle for Cerenkov radiation. Finally, according to Snell's law, a medium with negative refractive index should refract light in the same side to the normal on the interface as the incident ray [3].

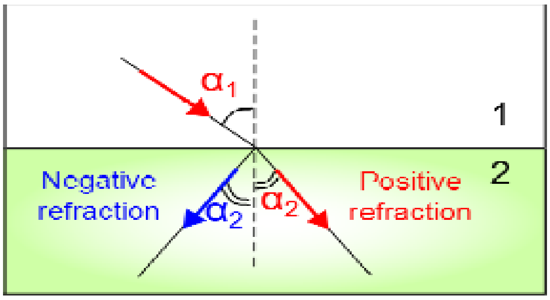


Fig. I.9 Negative and positive refraction angles.

II.7 Types of metmaterials

Generally, electromagnetic MTMs are classified into two classes: resonant and non-resonant metamaterials. Both resonant and non-resonant metamaterials have their own advantages and disadvantages.

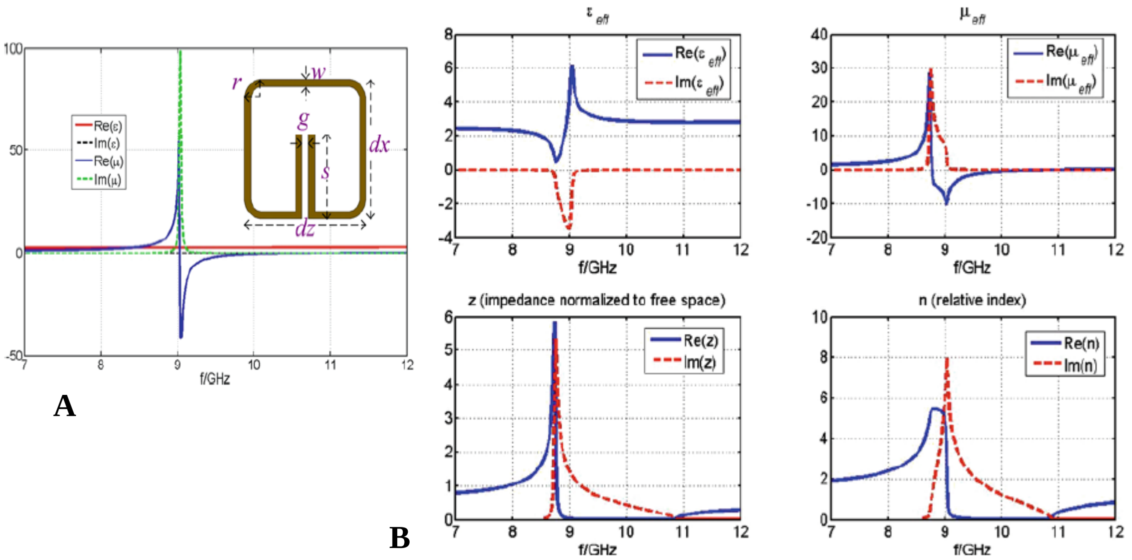


Fig. II.10 The constitutive parameters (permeability) of a periodic structure whose inclusion is SRR. (**A**) From the Drude–Lorentz model under the static and quasi-static limits. (**B**) From the S-parameter retrieval under full-wave simulations.

Fig. II.10(B) shows the material properties of a typical resonant metamaterial composed of SRR, as illustrated in the inset of Fig. II.10(B) from Fig. II.10(A), one clearly observes that both the permittivity and the permeability have a large dynamic range near the resonant frequency. When the frequency changes a little bit, ε and μ vary a lot. In the other word, when the size of SRR particle has a small change, the resonant frequency has a small shift, which results in significant change of ε and μ. Hence one can realize large dynamic-range material parameters using the resonant particle. This is the advantage of resonant metamaterials. However, one also notices from Fig. II.10(B) that ε and μ have a narrow bandwidth and a large loss near the resonant frequency, which are disadvantages of resonant metamaterials.

In fact, non-resonant metamaterials have also resonant frequencies, but they are much higher. Fig. II.11 demonstrates the constitutive parameters of a typical non resonant metamaterial composed of I-shaped inclusion (see the inset of Fig. II.11). It is clear that both ε and μ vary slowly with respect to the frequency and have very small loss. Hence the broad bandwidth and low loss are the big advantages of the non resonant metamaterial. On the other hand, when the size of I-shaped particle has a small change, ε and μ have also small change. Hence one can only realize small dynamic-range material parameters using the non-resonant particle, which is the disadvantage of non-resonant metamaterial.

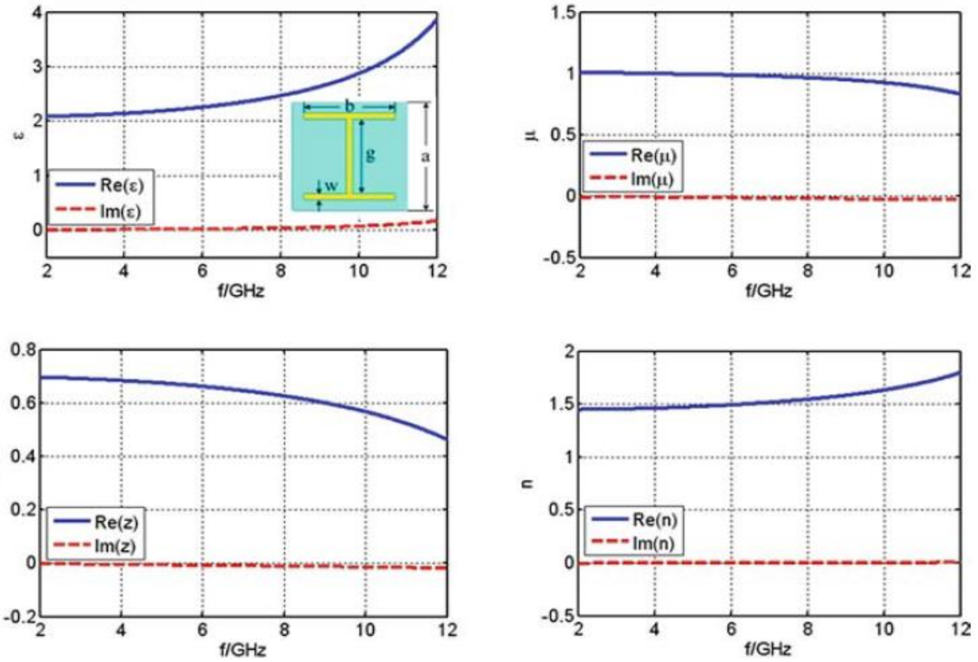


Fig. II.11 The effective constitutive parameters of a non-resonant metamaterial whose inclusion is I-shaped.

In the actual design of metamaterials, the choice of particle types depends on the device functions. For example, in the design of simplified circularly invisible cloak, large dynamic-range material parameters are required. Hence the resonant metamaterials had to be used. The cloak has a narrow bandwidth, and the invisible effect is not perfect due to the loss. On the other hand, in the design of ground invisible cloak (or invisible carpet), small dynamic-range material parameters are desired, and hence the non-resonant metamaterials had been chosen. The ground cloak has a broad bandwidth and small loss, and the invisible effect is perfect [4].

II.8 Applications of Metamaterials

Due to the exciting and unusual features, metamaterials have found and are finding a lot of applications or potential applications. Perhaps the most famous of them :

II.8.1 Super-lens

For LHM, The first possible applications of such artificially composed metamaterials are in optics due to their negative refractive index. John B. Pendry has claimed that lens made of metamaterials could focus light for objects less than wavelength λ in size to a geometric point. All lens utilizing natural materials known today cannot focus light on to an area smaller than the square wavelength of the light used to examine it (the diffraction limit). For instance, atoms are smaller than the wavelength of visible light. Hence, they cannot be seen using optical microscopes.

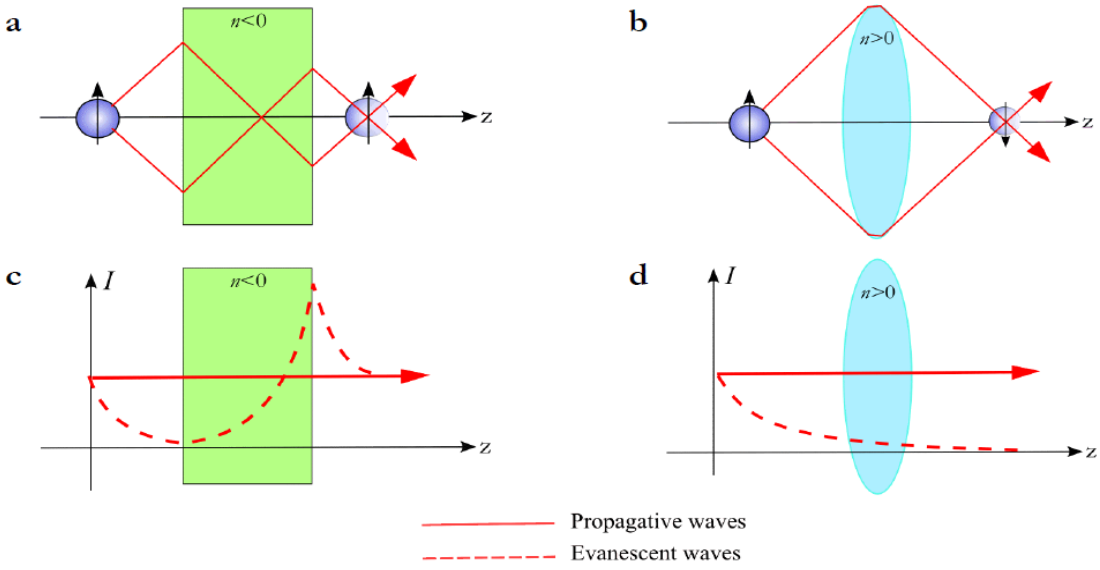


Fig. II.12 (a) Thick layer of MTM with negative refractive index focuses the light **(b)** A conventional convex lens that is able to collect only propagating waves **(c)** Inside negative index MTM slab evanescent waves are growing that means that the MTM lens fully restores the image behind the slab **(d)** The evanescent waves weaken through the conventional lens

Anything smaller than a wavelength of light such as atoms and molecules are out of reach for even the best available optical microscopes. But for such "super" lens one could literally see previously invisible objects like atoms [7].

II.8.2 Absorbers

A metamaterial absorber is a type of metamaterial intended to efficiently absorb electromagnetic radiation such as light. The metamaterial utilizes tiny geometric shapes to absorb both the electrical and magnetic properties of electromagnetic waves. Boston College—designed "perfect absorber of light" with metamaterials. This property of metamaterials can be incorporated into solar cells to enhance sensitivity for greater energy conversion. Future applications of metamaterial absorbers include emitters, spatial light modulators, camouflage and use in thermo photovoltaics [8].

II.8.3 Cloaking Devices

Metamaterials have provided basis to realize a practical cloaking device by successful demonstration of invisible cloaks experimentally in the microwave regime. If an object is covered with such a metamaterial then that will mean that light waves will flow around the object and hence, will not be detected. In 2009, a group of scientists announced cloaking at optical frequencies. In this case the cloaking frequency was centred at 1500nm (in infrared region). The metamaterial acoustic cloak is designed to hide objects submerged in water. Cloaking devices find their main application in stealth technology [8].

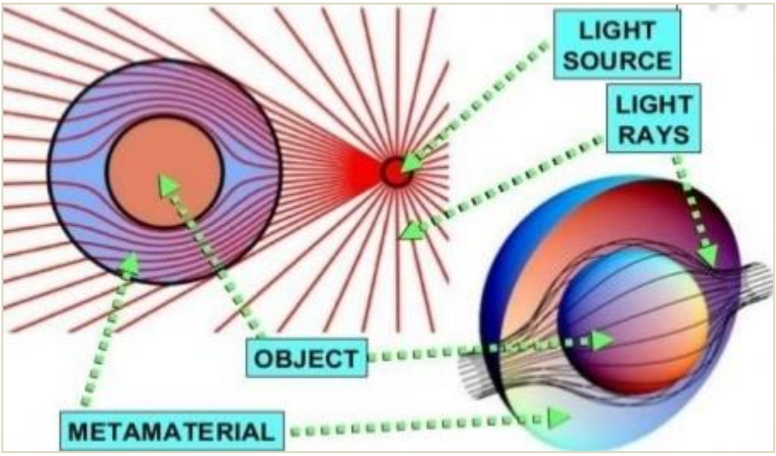


Fig. II.13 Cloaking.

II.8.4 Metamaterial as sensor

Metamaterial opens a door for designing sensor with specified sensitivity. Metamaterials provide tools to significantly enhance the sensitivity and resolution of sensors. Metamaterial sensors are used in agriculture, biomedical etc. In agriculture the sensors are based on resonant material and employ SRR to gain better sensitivity, In bio medical wireless strain sensors are widely used, nested SRR based strain sensors have been developed to enhance the sensitivity and described by Goran Kiti et .al (2012) [9].

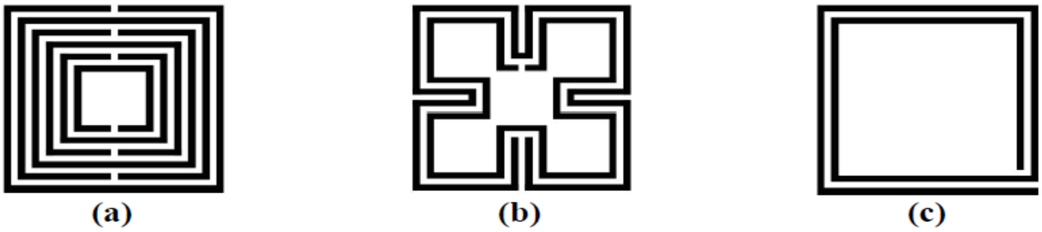
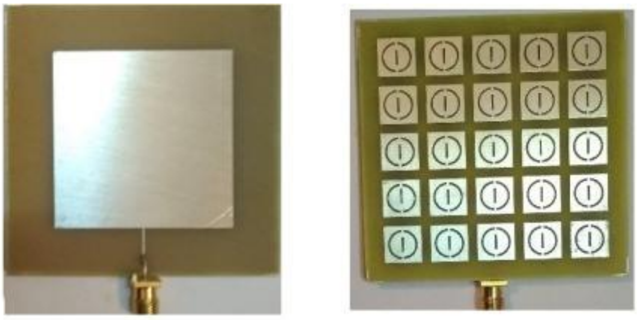


Fig. II.14: Metamaterial unit cells that are used for the sensor **(a)** Multiple SRR **(b)** Sierpinski SRR **(c)** Spiral Resonator

II.8.5 Metamaterials as antenna

One of the most important applications of metamaterials is antenna design. Due to the unusual properties of MTMs, antennas can be designed with novel characteristics which cannot be realized with traditional materials.

Metamaterials have been widely used in the design of microwave devices and antennas. A huge number of new devices and antennas have been fabricated with novel performances. However, due to the fast development of flexible portable devices such as mobile phones, laptops, wearable devices, etc., antennas with different tunable functions, based on variable structures, are still in urgent demand [10].



(a) (b)

Fig. II.15 Example of patch antenna **(a)** conventional patch antenna **(b)** Metamaterial patch antenna

II.9 Definition of antenna

An antenna is a device that converts electrical energy from electromagnetic energy during transmission or reception. An antenna can transmit in all directions (omnidirectional antenna) or in a defined direction (sectorial or directional antenna) [12].

II.10 Antenna Parameters [13]

II.10.1 Directivity

From the field point of view, the most important quantitative information on the antenna is the directivity, which is a measure of the concentration of radiated power in a particular direction. It is defined as the ratio of the radiation intensity in a given direction from the antenna to the radiation intensity averaged over all directions. The average radiation intensity is equal to the total radiated power divided by 4π. If the direction is not specified, the direction of maximum radiation is implied. Mathematically, the directivity (dimensionless) can be written as

$$D=\frac{U(\theta,\phi)}{D(\theta,\phi)_{av}}=\frac{4\pi U(\theta,\phi)}{P_t}=\frac{4\pi U(\theta,\phi)}{\oiint_{\Omega}\ U d\Omega}$$

where P_t is the total radiated power in W and U is the radiation intensity in W/unit solid angle. It is linked to the averaged radiated power density S_{av} (it has a unit of W/m2) by distance squared, that is $U = r^2 S_{av}$

II.10.2 Radiation Pattern

The radiation pattern of an antenna is a plot of the radiated field /power as a function of the angle at a fixed distance, which should be large enough to be considered far field.

The radiation pattern contains a lot of useful information about the radiation characteristics of the antenna, some cannot be quantified (such as the shape of the pattern) and some can be quantified. Some of the most important ones are: the half-power beamwidth (HPBW) of the main lobe, also called the 3dB beamwidth or just the beamwidth (to identify how sharp the beam is); the 10 dB beamwidth or first null beamwidth (FNBW) (another one capturing the main beam shape); the first side-lobe level (expressed in dB, relative to the peak of the main beam); the front-to-back ratio (the peak of the main lobe over the peak of the back lobe, another attempt to identify the directivity of the antenna); null positions (sometimes used for anti-interference and positioning).

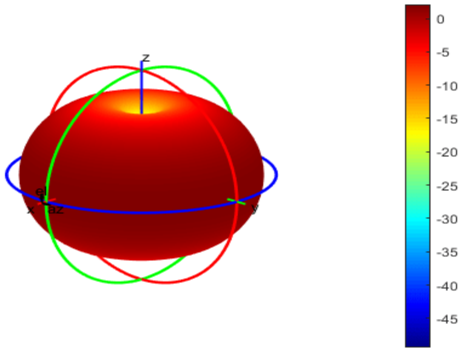


Fig II.16: The 3D Radiation Pattern.

II.10.3 Gain and Radiation Efficiency of Antennas

In practice, the total input power to an antenna can be obtained easily, but the total radiated power by an antenna is actually hard to get. The gain of an antenna is introducing to solve this problem. This is defined as the ratio of the radiation intensity in a given direction from the antenna to the total input power accepted by the antenna divided by 4π. If the direction is not specified, the direction of maximum radiation is implied. Mathematically, the gain (dimensionless) can be written as

$$G = \frac{4\pi U}{P_{in}}$$

where U is again the radiation intensity in W/unit solid angle and p_{in} is the total input power accepted by the antenna in W. It should be pointed out that the input power may be different from the input power accepted by the antenna when the feed line is not matched with the antenna. The voltage reflection coefficient $\acute{\Gamma}$ at the antenna input and the match efficiency

$$\acute{\Gamma} = 1 - \Gamma^2$$

II.10.4 PIRE

The antenna gain is often incorporated into a parameter called the effective isotropic radiated power, or PIRE, which is the amount of power that would have been radiated by an isotropic antenna to produce the peak power density observed in the direction of maximum antenna gain, that is $PIRE = P_t\,G$.

where Pt is the radiated power. The PIRE is often stated in dBi. The advantage of expressing the power in terms of PIRE is that the pathloss between the transmitting antenna and the receiving antenna can be obtained easily by the ratio of the transmitted to the received PIRE; this is why in the mobile radio industry PIRE is widely used.

II.10.5 Effective Height and the Antenna Factor

If an antenna is a wire-type antenna (such as a dipole), the effective height (h_e) may be used to replace the effective aperture. It is defined as the ratio of induced open-circuit voltage V on the antenna to the incident electric field E.

$$h_e = \frac{V}{E}$$

II.10.6 Polarization

Polarization is linear when the infinitely radiated field maintains a direction constant (rectilinear) over time, and it is circular when the end of the vector infinitely radiated electric field describes a circle as a function of time. The polarization can also be elliptical. Any elliptical wave can be considered as the vector addition of two perpendicular vectors out of phase in time of 90 °. These two components can be recovered by means of polarization antennas linear. Conversely, a linearly polarized electric field can be broken down into two vectors with opposite circular polarization [12].

II.10.7 Bandwidth

Many antenna parameters are functions of frequency. When the frequency is changed, the radiation pattern may also be changed, which may result in changes to the directivity, gain, HPBW and other parameters. Thus, it is important to ensure that the right parameters are chosen when the antenna bandwidth is considered [13].

II.11 Conclusion

In this chapter, we have provided a brief overview about metamaterials and their properties that distinguish them from the rest of materials found in nature, where it takes its properties from its shape and how its cells are arranged instead of taking it from its components. Because of its special properties, they have been widely used in the microwave and antenna applications.

Chapter III: Metamaterials based Wearable Antennas

Chapter III : Metamaterials based wearable antennas

III.1 Introduction

In this world of modern technology, wearable antennas based on metamaterials are essential for everyday use. They are used in wireless local area networks, mobile phones, and satellite communications. An antenna is a transducer that converts radio frequency (RF) fields into alternating current or vice versa. There are receiving and transmitting antennas for transmitting or receiving radio transmissions. Depending on their applications, antennas have different shapes and sizes. As an example: cell phones and laptops use small antennas (usually a printed one), television uses a dipole antenna, and RADAR systems use a wide variety of antennas. In order to improve technology in telecommunications, it will be necessary to replace traditional microwave antennas in many applications such as satellite communications, portable equipment and satellite navigation receivers by microstrip antennas. The latter finds its applications in various high-tech fields such as mobile communications, missile telemetry, and biomedical uses especially wearables. This is mainly due to the various advantages it offers, among which are light weight and ease of installation [14].

III.2 Metamaterials applied to antenna

The most metamaterials structures that used to improve the antenna properties are the high impedance surfaces (HISs) and artificial magnetic conductors (AMCs), since they can lead to the design of compact and low-profile antenna systems. In such a case, metamaterial designs are placed around or close to the antennas, although metamaterials can also be used in the feeding part of the antenna system, or even as a part of the antenna structure [15].

III.2.1 Unit cell of metamaterials [16]

The metamaterials applied in the antenna design can a single unit cell or an arrangement of multiple unit cells. Thus, the first step in designing the antenna metamaterials is to design and analyze the main factors affecting the resonance frequency, permittivity, and permeability of its unit cell. The design of unit cells of metamaterials is based on the calculation of size and simulation of unit cells, so that the parameters ε and μ of these unit cells will satisfy the requirements at the expected resonant frequency. Depending on the structure and size of each unit cell, we can obtain different ε, μ, and resonant frequencies f. For each unit cell type, the dimensions of unit cell can be adjusted to satisfy condition at resonant frequency. A unit cell is usually smaller than 1/10 of the operating wavelength, depending on the shape of the metamaterial, but the unit cell size is different.

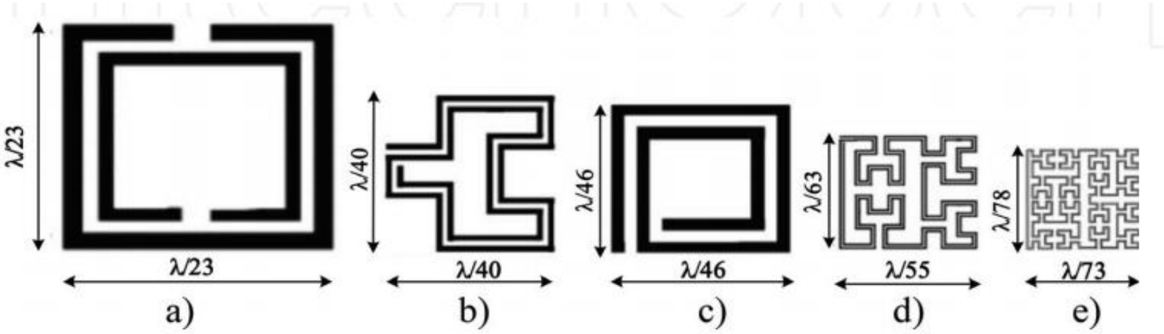


Fig III.1: A unit cell of an inclusion with the SRR (a), second-order Hilbert fractal inclusion (b), square spiral (c), third order Hilbert fractal inclusion (d), and fourth-order Hilbert fractal inclusion (e). Note that as the order of Hilbert fractal curve increases, the size of inclusion decreases.

III.2.2 The functions of metamaterials in antenna design

III.2.2.1 Metamaterials used as the antenna environment

Metamaterials are applied as the antennas environment, to improve their radiation properties by using the artificial magnetic conductor (AMC). It is a type of implemented metamaterial in several antennas and microwave design applications. By utilizing the unique characteristics of metamaterials which do not exist naturally, the performance of various microwave devices can be enhanced.

III.2.2.2 Metamaterials as part of antenna structure

Metamaterials can be used as part of the antenna structure, which aims to design a compact antenna size without deteriorating performance of its. In this case, the metamaterials are used with high permeability values ($\mu >> 1$) as a magneto-dielectric (MD) substrate of patch antennas. As a result, the size of the antenna is significantly reduced without using a high permittivity ($\varepsilon >> 1$).

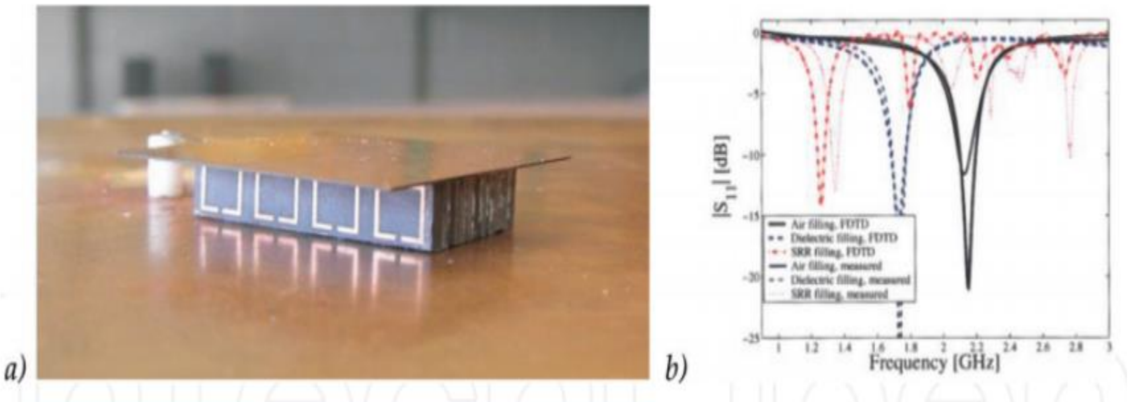


Fig III.2: Patch antenna with high-μ metamaterial substrate (a) and input impedance plots for different substrates air, dielectric, and magneto-dielectric (b).

III.2.3 The effects of applying metamaterials in antenna design

Using metamaterials in antenna design may lead to reduced size, improve gain, enhance bandwidth or to create multiband antenna. Depending on the technical requirements of the designed antenna, the metamaterials will be used as different functions of the antenna.

III.2.3.1 The metamaterials in improving gain of antennas

Low gain is a main disadvantage of small planar antennas, which must be overcome to satisfy transceiver systems overall energetic ling budget. In addition to using an array antenna, recently the metamaterial is a solution that has been applied in antenna design. In this case, the used metamaterials may be artificial magnetic conductors (AMCs) or artificial magnetic materials (AMMs). They are applied as the environment of the antenna in such a way as to arrange the unit cells of the metamaterials surrounding radiated elements of the antenna, or using one or more superstrates above or below the radiated elements or using such as metamaterials as the loading of the antenna.

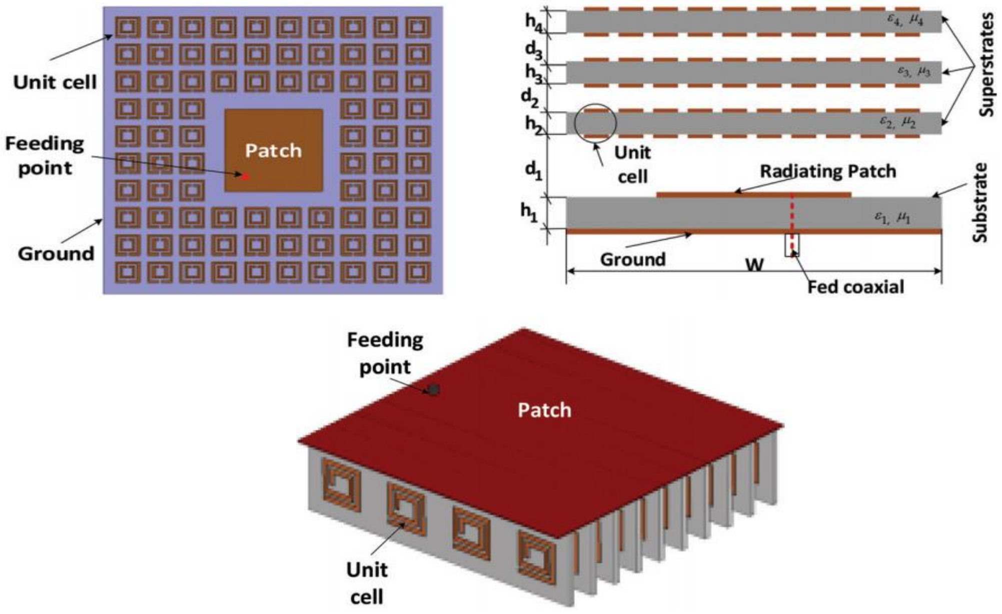


Fig III.3: Models of metamaterials application in improving the power gain of the antennas: unit cells surrounding the radiated patch, metamaterials as superstrate, using the metamaterials as antenna loading.

III.2.3.2 The metamaterials in reducing the size of antennas

There are many technical solutions that have been used to design compact antennas such as high-permittivity dielectric substrate of microstrip antennas, shorting pins, shorting walls, inserting some disturbances into antenna structure, applying the fractal geometry, etc. Recently, many designers have used metamaterials as a defected ground structure (DGS) to reduce the size of the antenna. In this case, the unit cells of the metamaterials have unusual properties at the resonance frequency of the designed antenna; the dimension of these unit cells is equal to the size of the removed parts of the DGS.

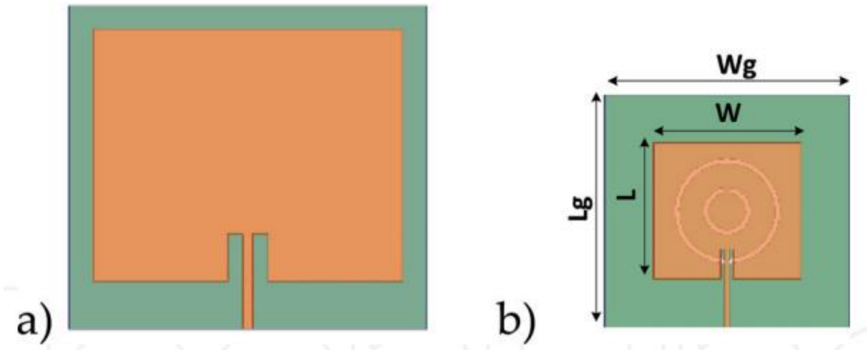


Fig III.4: Comparison of the size of microstrip patch antenna MPA without loaded CSRR (a) and with loaded CSRR (b) for GSM system.

III.2.3.3 Use of metamaterials to enhance the antenna frequency bandwidth

In addition to the benefits of using metamaterials to design the antennas mentioned above, it is also used to enhance the antenna frequency bandwidth. To achieve this goal, the metamaterials are used as components of the antenna or a superstrate placed above the radiation surface (like the method of improving the antenna gain). Unit cells of metamaterials can be placed on top or under bottom of the superstrate. The bandwidth of this antenna depends on the number of unit cells as well as the distance of the superstrate to the radiation surface. The application of metamaterials in the antenna design resulted in a good improvement in the antenna bandwidth compared to other antennas.

III.2.3.4 Use metamaterials to get multiband

From the need to integrate multiple functions (many communications systems operation) on single devices, multiband antennas are more interested. The use of metamaterials in antenna design is an attractive trend not only to reduce size, improve the power gain, enhance bandwidth, but also to design multifrequency-band antennas. The unit cells of metamaterials can be used as radiation components, a part or loaded part of the ground plane of antenna. Because, MTMs can support negative refraction indexes at resonant frequencies and unit cell structures of symmetric pairs. This can be used to design multifrequency antennas with smaller dimensions than traditional one. Metamaterial can be combined with a conventional or fractal microstrip antenna to create multiband antenna, in which the antenna size is determined by the lowest frequency.

III.3 Reconfigurable antenna

III.3.1 Definition

Reconfiguring an antenna is achieved through deliberately changing one or more properties of the antenna, such as its frequency, polarization, or radiation characteristics. This change is achieved by many techniques that redistribute the antenna currents and thus alter the electromagnetic fields of the antenna’s effective aperture. Reconfigurable antennas can address complex system requirements by modifying their geometry and electrical behavior, thereby adapting to changes in environmental conditions or system requirements (i.e., enhanced bandwidth, changes in operating frequency, polarization, and radiation pattern) [17].

III.3.2 Reconfigurability techniques

Reconfigurability in antenna systems is a desired feature that has recently received significant attention in developing novel and pioneering multifunctional antenna designs. Compared to conventional antennas, reconfigurable antennas provide the ability to dynamically adjust various antenna parameters. The active tuning of such antenna parameters is typically achieved by manipulating a certain switching behavior.

Reconfigurable antennas reduce any unfavorable effects resulting from co-site interference and jamming. In addition, they have a remarkable characteristic of achieving diversity in operation, meaning that one or multiple parameters, including operating frequency, radiation pattern, gain and/or polarization, can be reconfigured with a single antenna. The use of reconfigurability in coordination with a self-similar antenna leads to a considerable improvement in antenna performance. This is because not only a wider selection of frequencies is achieved, but also similar radiation properties for all designed frequency bands are obtained.

Electronic, mechanical or optical switching may be employed with reconfigurable antennas. Nonetheless, electronic tunability is more frequently used because of its efficiency and reliability especially in dynamic bandwidth allocation. Electronic reconfigurability is often attained using lumped components such as PIN diodes, FET transistors or RF MEMS switches. Compared to PIN diodes and FET transistors, RF MEMS switches have better performance in terms of isolation, insertion loss, power consumption and linearity [16].

III.3.2.1 Variable capacity

A variable capacity is a diode which behaves like a capacitor whose capacitance value varies with the reverse voltage applied to its terminals Figure; when we change its bias voltage, we change the value of this ability. Although varicap diodes have a certain ease of integration and high continuous agility, the losses introduced by this component are sometimes significant and the bias voltages can reach 30V. In addition, the complexity of the circuit polarization increases with the number of varicap diodes required to make the antenna reconfigurable. These diodes are often used to produce agility [19].

III.3.2.2 PIN diode

A PIN diode acts as a switch. When it is reverse biased it is non-busy (state OFF), but a polarization in the forward direction makes it passable (state ON). Yang and Rahmat Samii presented in [22] a microstrip antenna on which is cut a vertical slot and on which a PIN diode is added.

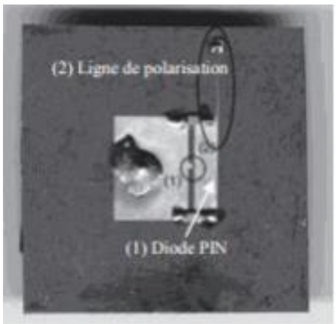


Fig III.5: Printed antenna with slot and PIN diode on the roof.

III.3.2.3 MEMS (Micro electromechanical system)

A MEMS is a microsystem comprising one or more mechanical elements, using electricity as a source of energy, in order to perform a sensor function and / or actuator; partly ensured by the very shape of the structure.

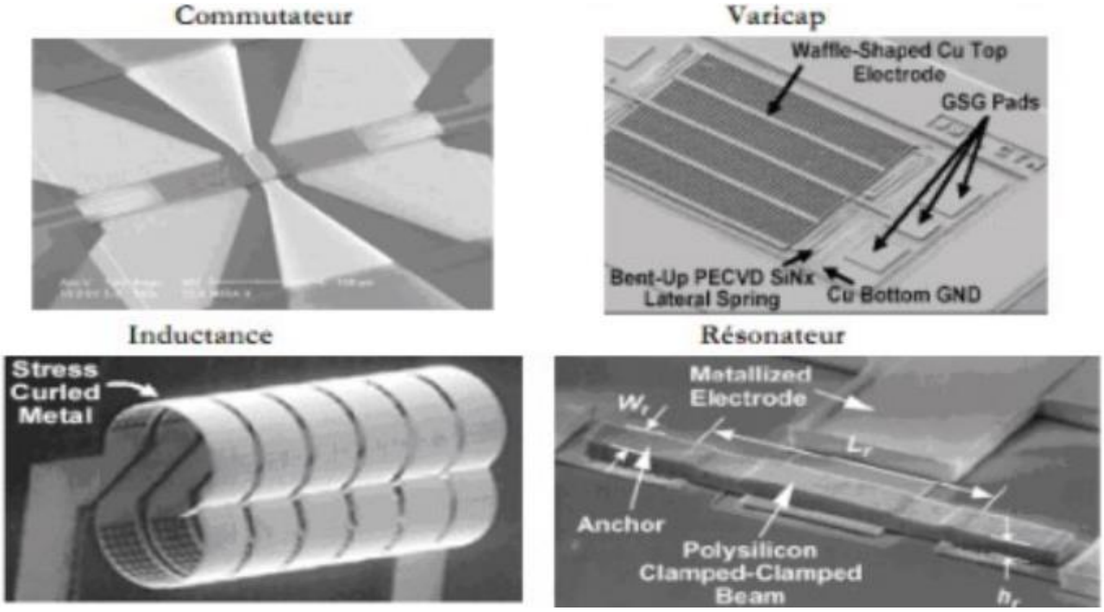


Fig III.6: Examples of MEMS components.

According to their design, the MEMS can be used for various functions. Typically, they can replace capacities in antenna structures or switches in the same way as varicap or PIN diodes. However, they need a very high activation voltage, but as they hardly consume any current, the losses are very low.

III.4 Choice of reconfigurable antenna technology

Nowadays, the use of printed antennas has become almost widespread in all communication systems due to the wide variety of geometric shapes present can take and that make them applicable to different integration situations. these antennas are light in weight, space saving and inexpensive. added to this, a production in easy mass, Radiation in linear and circular polarization possible, multi-band antennas, multi-polarizations, compatibility with hybrid circuits, Power supply networks and adapters manufactured simultaneously with the antenna. Nevertheless, these antennas have drawbacks, namely: narrow bandwidth (1 to 5%), low gain, circuit power supply sometimes very complex, low power…. etc [17].

III.5 Future of reconfigurable antennas

We expect future smart reconfigurable antennas to be completely multifunctional and software controlled with machine learning capabilities that can detect changes in their RF environment and react accordingly. Applications such as cognitive radio will be implemented based on a new generation of communication protocols and antenna systems. The key advantage for such application will be the efficient use of frequencies and even the utilization of radiation pattern reconfigurability and polarization diversity to transmit over already busy frequencies. The use of reconfigurable antennas in MIMO channels will not only improve the channel capacity but also will increase the efficiency of such channels and reduce their costs. Finally, the merging of deployable and reconfigurable antennas will open new frontiers in the design of antennas for space communications.

III.6 Metamaterial based reconfigurable antenna

The most important objective of the thesis, which is a metamaterial-based reconfigurable antenna that provides beam switching capability in its azimuth plane, has been realized. To accomplish this objective. Reconfigurable metamaterial unit-cell used in the form of a two-dimensional array in the structure of a controllable medium in front of the antenna radiator in its plane [20].

We use diodes at the end of each branch of unit cell and monitor its behavior connected or disconnected (ON/OFF). This is what we will discuss in the next chapter.

III.7 Types of metamaterials based antennas

Among the most important types of antenna loaded with metamaterials:

III.7.1 Electrically small antennas based on zeroth resonant mode

Electrically small antennas (ESA) are desired for mobile communication systems. In a traditional design, the performance of the antenna is related with its size so the antenna usually has dimensions in the order of the operating wavelength. In a medium whose refractive index is near zero, shows an operating wavelength that is infinite at an arbitrary designed frequency. This phenomenon is named zeroth resonant mode. Since the wave number in this antenna is zero, in theory, the physical size of the antenna can be made independent of its working frequency.

III.7.2 Dual-band and multi-band antennas

Normal dual-band antennas are realized with different resonant structures, or different resonant modes in one structure. The main disadvantage of this technique is that the field distributions in these structures can hardly be the same in both bands. This means that the radiation patterns in the operating bands are different. Since metamaterials can support a negative refractive index, the resonant modes can be selected as a symmetric pair, i.e. so-called negative and positive modes. The field distributions of these two modes can be very similar, and thus also the radiation patterns.

Negative and positive modes can be designed together with a zeroth-order mode. This yields a multi-band antenna with a specific pattern for each mode. An extra advantage of a metamaterial-loaded multi-band antenna is the fact that its size is usually smaller than in a traditional design, where the size is decided by the lowest operating frequency.

III.7.3 Antenna lenses and polarizers

Dielectric lenses can be used to improve the directivity and gain of an antenna. However, the cost to fabricate a 3D lens is large. Further, the location of the lens should be carefully chosen in relation with the phase centre of the antenna. A metamaterial lens can be formed by a flat 2D structure. Their manufacturing cost is much lower. They can even be integrated with the planar antenna structure to reduce the profile and size of the antenna system.

A polarizer can be based on a chiral medium which has the capability to transform a linearly polarized wave into a circularly polarized wave. This opens a way to design circularly polarized antennas based on existing linearly polarized antennas.

III.7.4 Other antennas and structures involving metamaterials

There are a lot of other types of antennas and structures involving metamaterials, e.g. leaky wave antennas, magnetodielectric microstrip antennas, ultra wide band (UWB) antennas with notched bands, metamaterial based isolators, low profile planar reflectors, series power divider , dual-band splitters and delay lines, etc.. All of these designs have a relatively better performance than the corresponding conventional designs.

III.8 Metamaterials based Wearable antenna

Wearable electronic systems are very attractive for e.g. continuous medical monitoring, emergency rescue services, care for children and the elderly, etc. As a consequence, the concept of Wireless Body Area Networks (WBAN) has become a more widespread research topic. As a critical component of these systems, the wearable antenna plays a key role for the wireless communication on or off the body. However, the design flowchart for wearable antennas is quite different compared to the traditional ones. First, the electromagnetic coupling between the human body and the antenna will influence the performance of the antenna. Secondly, different deformations, e.g. bending, crumpling, and wrinkling, need to be considered in the antenna design. Considering the isolation between the antenna and human body, a piece of metal plane is usually required to shield one from the other. The microstrip patch antenna topology is a good candidate for wearable devices, since it is usually low profile and easy to fabricate. The large ground layer under the patch reduces the coupling between the human body and antenna, and enhances forward radiation. When a dual-band function is needed, the patch antenna may be loaded using slots, lumped components, parasitic patches, or be stacked [10]. We will see an example of this in chapter three.

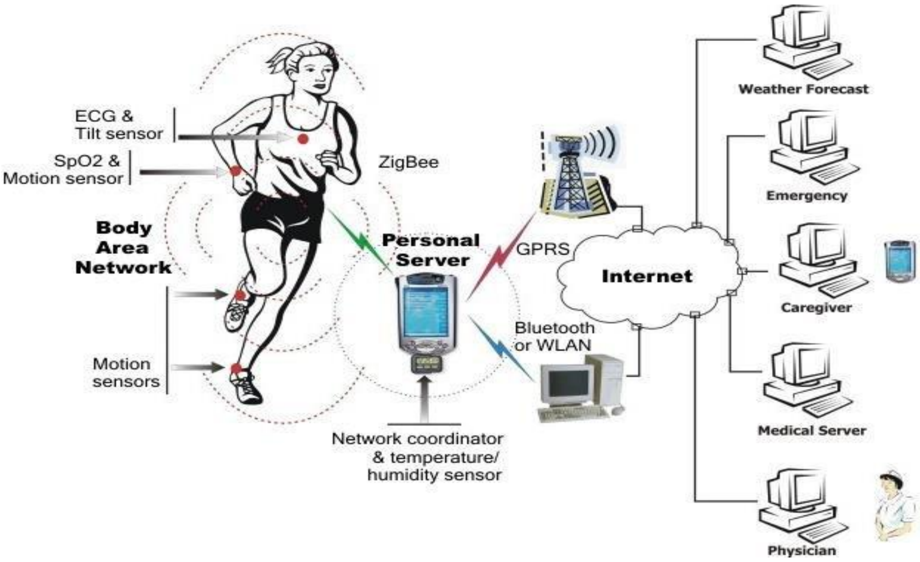


Fig. III.7 BAN medical surveillance networks.

Networks centered on the person are divided into three categories that depend on the position of the antennas relative to the body [11]:

- Communications of systems or apparatus from the outside of the body to the body or **off-body** communications. In this link the propagation channel is the surrounding space and a single antenna is placed on the human body,
- Communications on the body of networks and portable systems or **on-body** communications. Most channels are on the surface of the body and all the antennas are on the body,

- Communications of medical implants and sensor networks inside the body or **in-body** communications. These implants communicate with an antenna which is on the body, the propagation channel being the inside of the human body.

The design of the geolocation antennas enters the off-body communications systems category because the antenna directly receives signals from the satellite giving the positioning information.

The type of antenna varies according to the working conditions for which are intended. For wearable antennas the patches are very widely used because they are compact but above all directive with maximum radiation in the direction perpendicular to the antenna. In addition, thanks to their ground plane, the antennas emit little radiation in the human body. The shapes of the patches can be square, rectangular, triangular, or circular. For multi-band or broadband operation, slits are made in the patches.

Antennas with omnidirectional radiation, such as dipoles, monopoles, butterfly knots, admit low gains due to their radiation pattern and moreover, radiate into the human body when they are in its proximity. The only way to isolate this harmful radiation is to use a ground plane that acts as a reflector. The problem arises, however, when the antenna is brought too close to the ground plane. The currents flowing on the ground plane in phase opposition to the current on the antenna, then annihilate any radiation from the antenna. The only possibility of using this ground plane in the presence of an antenna is to place it at a distance of $\lambda / 4$ from it, as for a reflector. In this way, we obtain an improvement in the performance of the antenna on the radiation pattern with a decrease in the back radiation. The main drawback appears for low frequency use. This gives significant lengths for the integration of the antenna on the body or in a garment. This is where **metamaterials** come in, which have very specific properties on the phase of the reflection coefficient of the surface. These materials consist of periodic metallic patterns of length less than the wavelength. These structures are called HIS High Impedance Surface type MTM. The first textile antenna based on HIS type MTM was designed in 2001. The structure is a patch on an electromagnetic band gap surface, made up of 6 * 6 square patch elements on which a 2.4 MHz resonant patch antenna is mounted (antenna shown in Fig. III.8). The use of such a surface in the presence of the patch allows the size of the antenna to be reduced, making it easier to integrate into clothing.

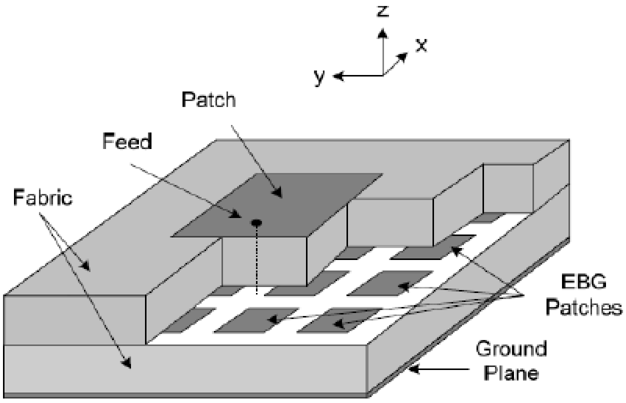


Fig. III.8 Metamaterial-based patch antenna.

III.9 Conclusion

In this chapter it was about the reconfigurable antenna and its application in the wearable antenna based on metamaterials, this part presents the definition of the reconfigurable antenna and some of the techniques used to achieve the reconfiguration. Finally, the types of metamaterials and their applications in the wearable antenna are discussed.

Chapter IV: Reconfigurable Metamaterial Antenna with Defects

Chapter IV: Reconfigurable Metamaterial Antenna with Defects

IV.1 Introduction

The metamaterial antennas are widely used in modern communication systems, due to the new additions provided in this field, as we find it has many applications such as improvements in the antenna's parameters, including wearable antennas applications for its ease of fit to the curves of the human body.

In this chapter we will simulate a metamaterial antenna to emulate a conventional antenna studied in [1] for wearable antenna applications. At first, we simulate an agile metamaterial unit cell which has two different states: If the unit cell is in the first stat (ON-state) the metalaterial behaves as a conductive medium with a refractive index near to zero, other weise (the unit cell is in the second state (OFF-state)), the metamaterial behaves as an dielectric medium with a refractive index greater than one . The agile unit cell is a metallic cross shape conductor printed on a FR4_epoxy dielectric substrate. The agility property of the unit cell get it by installing an external switching system command at the ends of the cross branches, such as PIN-diodes.where the unit cell can take one of two possible states, the first is ON-state which the metamaterial unit cell becomes a connected cross type and the metamaterial behaves as a conductive medium, the second one is OFF-state which the metamaterial unit cell becomes a disconnected cross type so the metamaterial behaves as an dielectric medium. Based on these two unit cell types (connected or disconnected), we'll emulate the conventional antenna where the conducting parts are replaced with connected type unit cells while the dielectric parts are replaced with disconnected unit cell type. During this work, we have progress in five stages, in each stage a new slot is added that leads to change the shape inside the patch to obtain at the last stage a dual-band antenna operating at ISM frequency range. The different slots configurations have different frequencies making the emulated metamaterial antenna agile.

In this chapter, We re-simulat the dual band rectangle patch antenna [1] to cover the lower and upper ISM band. The chapter is divided in two sections, the first presents the metallic antenna with its dimensions and simulation results. The second section, we describe the behavior of metamaterial unit cell (connected / disconnected) from it we'll emulate the metamaterial antenna then we'll compare between the reference antenna and the metamaterial one, using the simulation software HFSS (high-frequency structure simulator).

ISM band: **I**ndustrial, **S**cientific and **M**edical bands [902-928 MHz and 2400-2480 MHz] [1].

IV.2 The proposed antenna

IV.2.1 Metallic antenna design

The proposed antenna for ISM applications is a metal rectangular patch as Fig IV.1 with a width $W_p = 64mm$ and a length $L_P = 41.4mm$ a thickness $t = 0.035mm$ the patch is loaded with several slots and with specific dimensions as represented in the table 1. It is printed on FR-4 substrate of thickness $h = 0.8\ mm$, loss tangent $tan\ \delta = 0.02$ and dielectric constant $\varepsilon_r = 4.4$. FR-4 dielectric substrate is used due to its easy availability, however, the antenna can be designed on any flexible substrate having the same electrical properties [1].

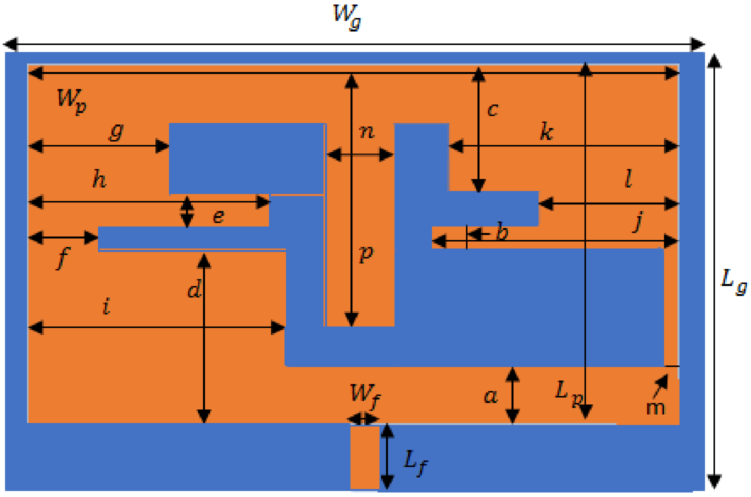
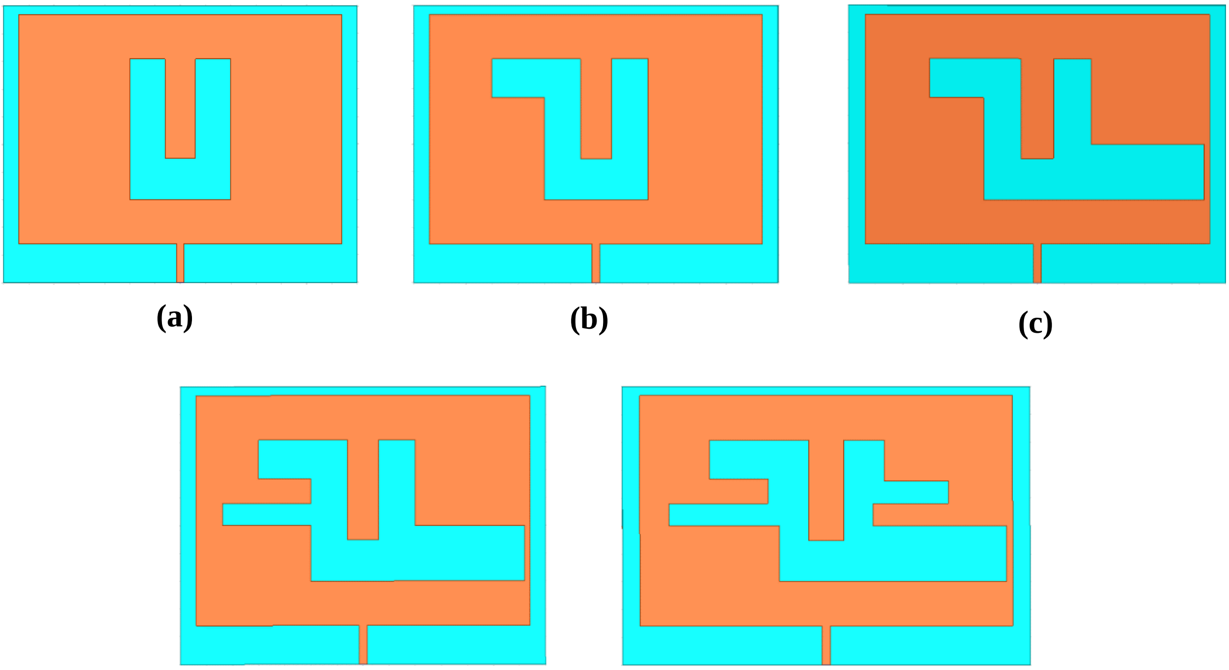


Fig IV.1: Proposed reference metallic antenna.

Tab IV.1 Metallic antenna dimensions.

Parameters	Values (mm)	Parameters	Values(mm)	Parameters	Values(mm)
L_p	41.4	d	18	i	24
W_p	64	e	4	j	24
L_g	50	L_f	7	k	22
W_g	70	W_f	1.5	l	11
a	8	f	5	m	1
b	4	g	12	n	6
c	15.4	h	22	p	26
d	18	m	1		

As we mentioned earlier, the main objective of designing this antenna it is to achieve the dual-band propriety. To achieve this, we loaded the patch with several slots (defect) in five steps, as described in the reference antenna [1] as shows in the Fig IV.2, and monitoring the resonant frequency with each stage until the desired frequency is obtained, for the ISM bands.



(a) **(b)** **(c)**

(d) **(e)**

Fig IV.2: Design steps of the proposed antenna.

IV.2.2 Description of Metamaterial unit cell

The cross unit cell is formed by two printed dipoles at 90° to each other. This structure is arranged in a periodic way to constitute the metamaterial layer.

In this work, we use an agile metamaterial unit cell that can controlled through an external switching system which is installed into each end of the crosses branches [21].

The unit cell used in this work is a metallic cross with a thickness of $t = 0.035\,mm$, width $w = 0.35\,mm$, and a length of approximately $\lambda / 125$ equal to $L = 1\,mm$ which represents the period of unit cell repetition along the XY plane, the reason for choosing this value is justified in the homogeneity hypothesis that requires the selection of a period that is at least equal to $\lambda / 7$, so that the electromagnetic waves can see the medium as a homogeneous substance. This cross is placed on a uniform FR4-type epoxy dielectric substrate with thickness $h_s = 0.8mm$ and dielectric constant $\varepsilon_r = 4.5$. The geometry and the boundary conditions applied in the unit cell are shown in Fig IV.3.

The agility behavior appears when we use one unit cell can switch between two types connected or disconnected based on an external switching command system such as PIN diodes that has two states (ON/OFF) which are installed in the gaps situated between two adjacent unit cells as presented in Fig IV.3-b.

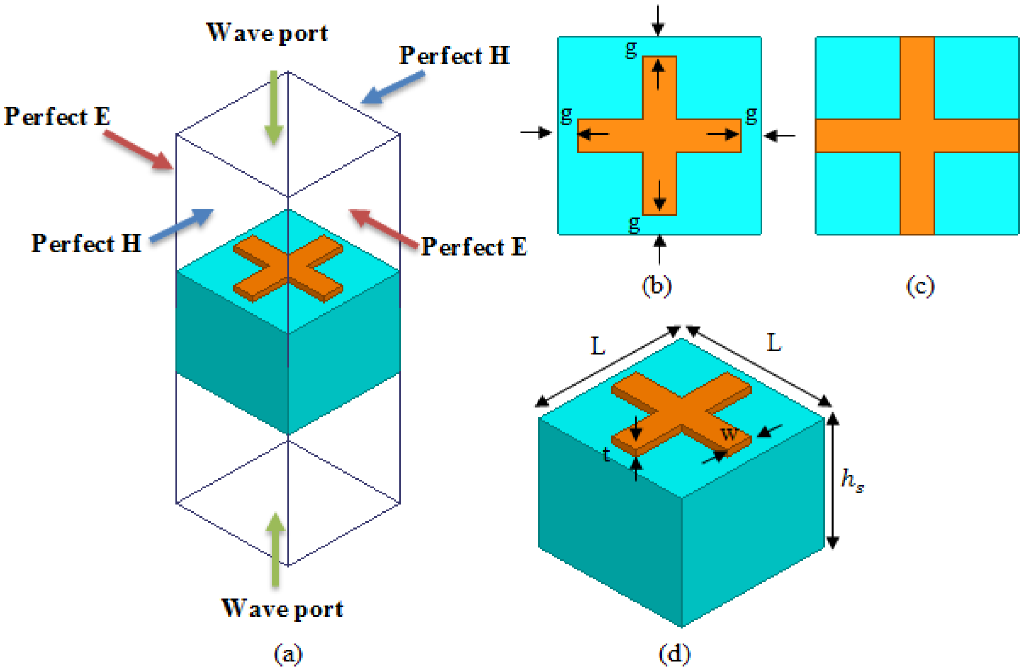


Fig IV.3: Metamaterial unit cell **(a)** boundary conditions applied, **(b)** top view of disconnected type, **(c)** top view of connected type, **(d)** 3D view of unit cell.

IV.2.2.1 Metamaterial Unit Cell Type Connected

The first metamaterial type is obtained when the switches are open (OFF-stat) where each cross is disconnected with his four neighbors and the metamaterial behaves as a dielectric medium. The effective constitutive parameters of the metamaterial type connected cross are depicted in Fig IV.4.

We observed that in the real part of the effective refractive index metamaterial connected cross-type is close to zero, and the real part of the effective permittivity is negative, but the imaginary parts it is close to zero regarding of permittivity and permeability but it is large in the effective refractive index, so we can say the effective medium behaves like a conductive material.

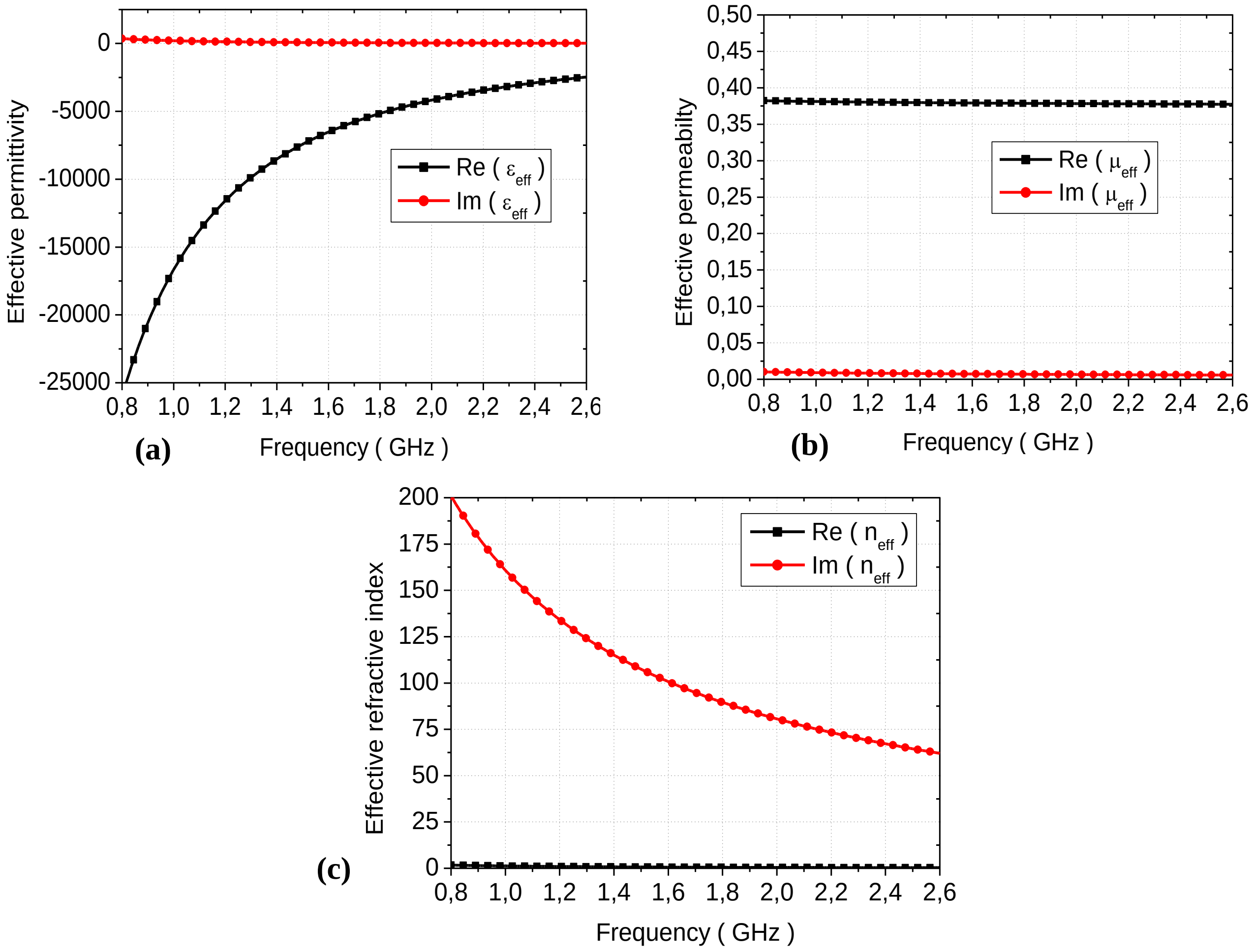


Fig IV. 4: **(a)** Effevtive Permitivitty, **(b)** Effevtive Permeability, **(c)** Effevtive refractive index of the metamaterial connected cross type.

IV.2.2.2 Metamaterial Unit Cell Type Disconnected

The second metamaterial type is obtained when the switches are closed (ON-state) the periodic structure become based on connected type when each cross is connected to four neighbors and the metamaterial behaves as conducting medium. The Fig IV.5 represents the effective constitutive parameters of the metamaterial type disconnected cross.

According to the result of the metamaterial disconnected cross type we observed that all imaginary parts are close to zero, and the real part of the refractive index is greater than unity therefore the medium behaves like a dielectric effective medium.

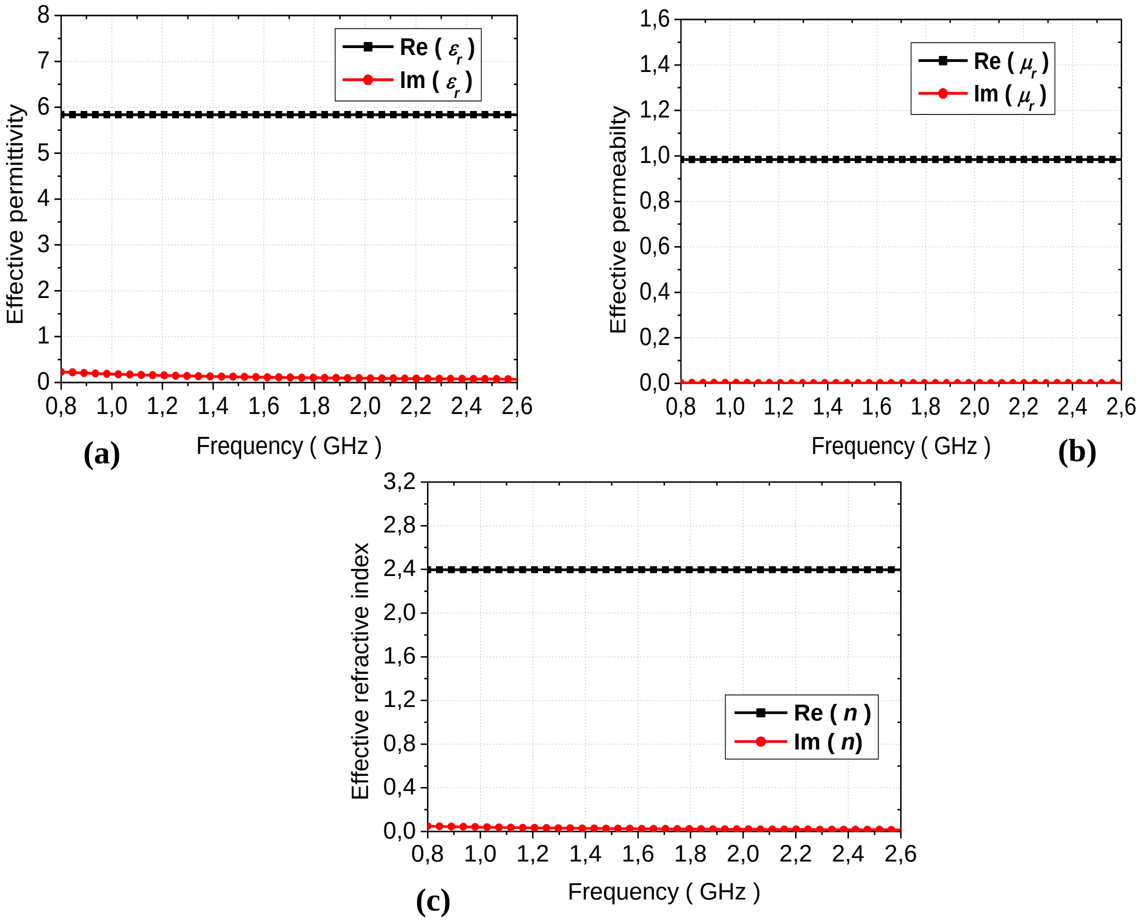


Fig IV.5: (a) Effevtive Permitivitty ,(b) Effevtive Permeability,(c) Effective refractive index of the metamaterial disconnected cross type.

IV.3 Metamaterial Antenna

We saw the agile unit cell in the previous section, which was used to design the dual band metamaterial antenna. In this section, we replace the top part of the patch antenna with a grid of unit cells of two different types, connected and disconnected At the first to imitate the conventional with metamaterial antenna the metallic top part is transformed into a grid of metamaterial unit cell connected type, whereas all spaces within (slots) and around the patch are transformed into a metamaterial unit cell disconnected type as Fig IV.6 shows.

We simulate two metamaterial antennas: in the first the substrate is completely covered with metametrial unit cells to occupy a surface equal approximately 3486 unit cell^2, which is denoted by " metamaterial antenna A", and the second we only transform the patch and the slots within it to metamaterial cells occupy a surface equal approximately 2624 unit cell^2 (Fig IV.7-**(e)**). The feed line is kept as a metal plate throughout all steps. Because there is congruence between the two results as the Fig IV.9 demonstrates where we noticed that each of the tow antenna are loss return at -23 dB in 2.4 GHz, from that we chose the second antenna (Fig IV.7-**(e)**) to make the simulation process easier

In the same way we did in the reference antenna to get a dual band. We load slots in five stages into the patch as the Fig IV.7 shows, with each stage replacing the slots in the reference antenna with a grid of metamaterial unit cell type disconnected and the conductive part with a grid of metamaterial unit cell type connected.

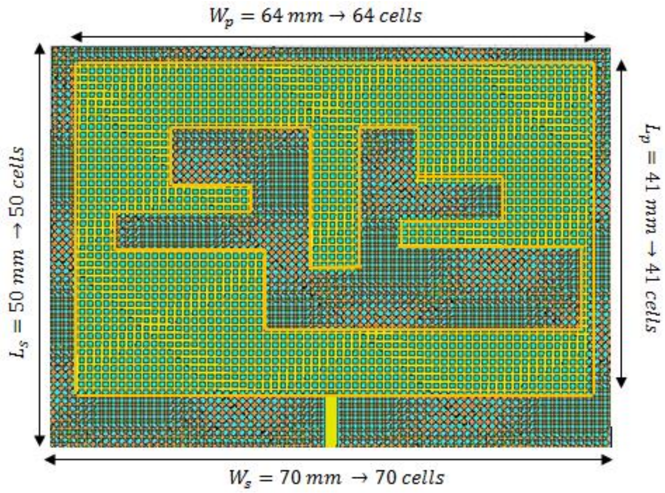


Fig IV.6: Metamaterial antenna A

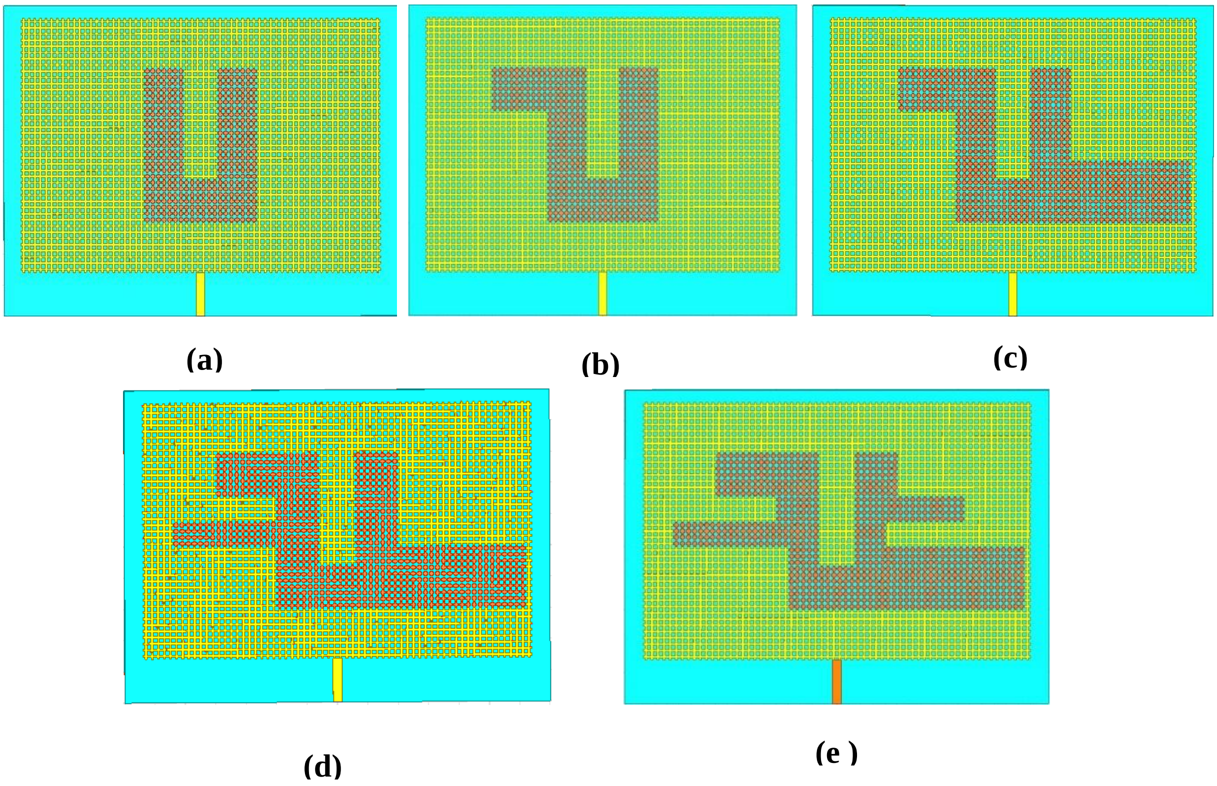


Fig.IV.7: Metamaterial antenna with five stages.

IV.4 Results and Discussion

In step 1, U-shape slot is introduced in the center of the rectangular patch as illustrated in FigIV.2-(a). The antenna resonates at 1261 MHz and 1786 MHz. In step2, as illustrated in FigIV.2-(b), a stub is formed on the left side of the U-shape slot, which shows a shift of 99 MHz and 9 MHz in the lower and upper resonating frequency band, respectively, so the resonant frequencies (1162 MHz-1777 MHz). The next slot loaded in the antenna in step 3 was created on the lower right side of the U-shape on the lower right side of the U-shape slot as shown in Fig IV.2-(c) here the antenna resonant at (1008 MHz - 1840 MHz). In step 4 another slot was introduced on the left side of the U-shape slot, shown in Fig IV.2-(d), the lower band shifts to 936 MHz (72 MHz) and the upper band shifts to 2455 MHz (615 MHz). The last step, the antenna was finally modified by inserting a small stub on the right side of the U-shaped hole to obtain the required frequency bands as shown in Fig IV.2-(e) which keeps the upper resonating frequency the same as of step 4 “ 2455 MHz ”, while a slight change appears at the lower resonant frequency range (shifted 9MHz to the left).

The curves in Fig IV.8 represent a comparison of the reflection coefficients of the five steps performed on the antenna proposed in the reference with the results of our re-simulation, where a shift appears in some cases due to the fact that the reference's results were obtained via CST software while our results were obtained from HFSS software. The comparison results are summarized in Table IV.2.

Tab IV.2 Summarization of the five steps antenna configuration comparison between the reference and our antenna.

Steps	Band width Reference antenna $f(MHz)$	Band width Our antenna $f(MHz)$	Return loss (reference antenna) $\|S_{11}\|$ (dB)		Return loss (Our antenna) $\|S_{11}\|$ (dB)	
			Lower	Upper	Lower	Upper
1	1222-1721	1261/1786	-25	-13	-19.27	12.78
2	1119/1720	1162/1777	-29.88	-15.67	-19.14	11.52
3	987/1805	1008/1840	-15	-7	-17.03	10.58
4	923/2408	936-2455	-25.1	-14	-23.87	14.08
5	918/2450	927/2455	-22	-44	-19.41	18.71

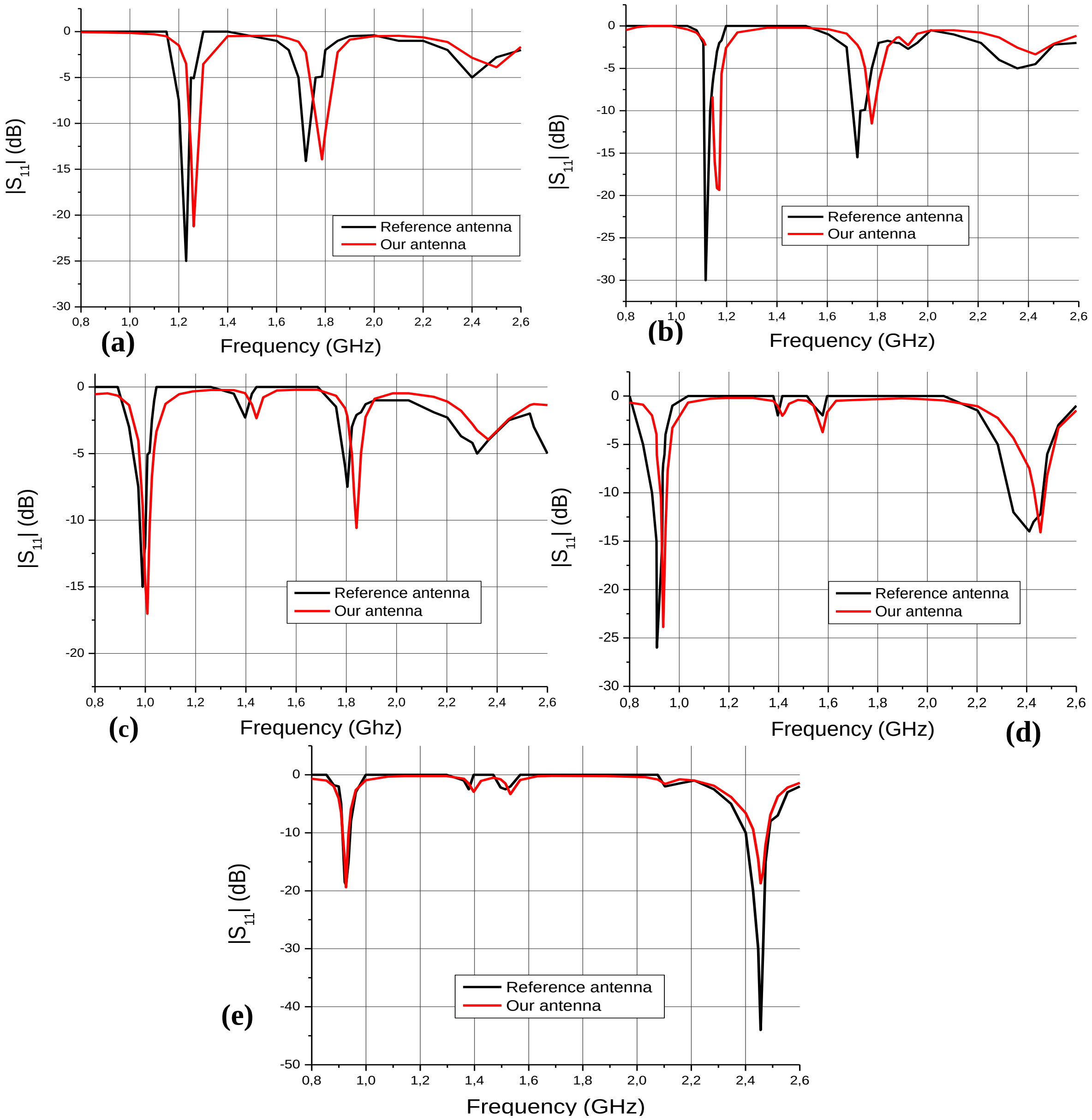


Fig III.8: Reflection Coefficients of the design steps.

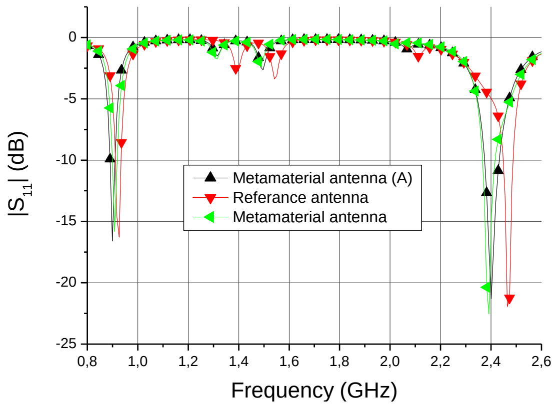


Fig IV.9: Comparison of the reflection coefficients between the Reference, Metamaterial and Metamaterial (A) antenna.

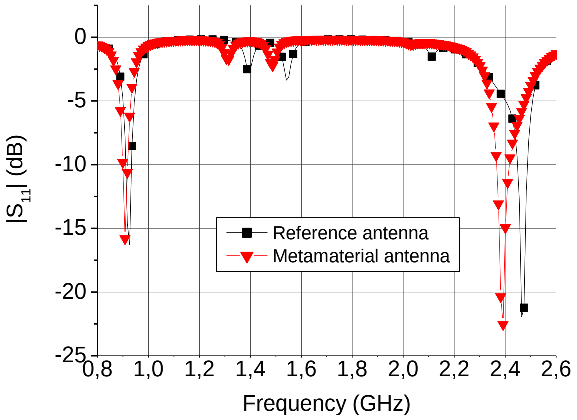


Fig IV.10: The Reflection Coefficients Comparisons between the Reference in the step 5 and Metamaterial Antenna.

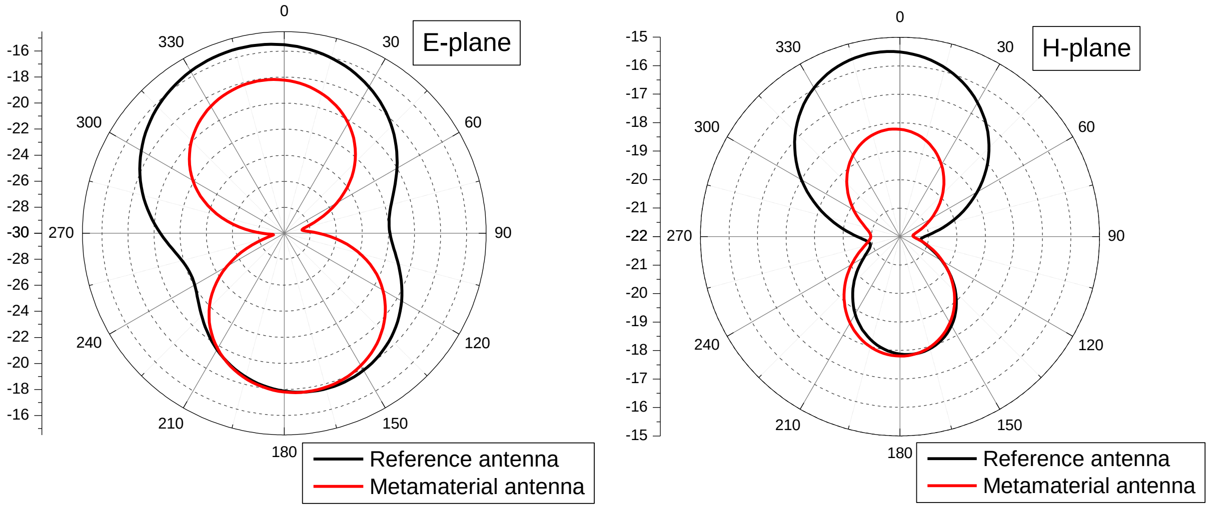


Fig IV.11: The Radiation Pattern Comparisons between the Reference in the step 5 and Metamaterial at 0.9 GHz frequency.

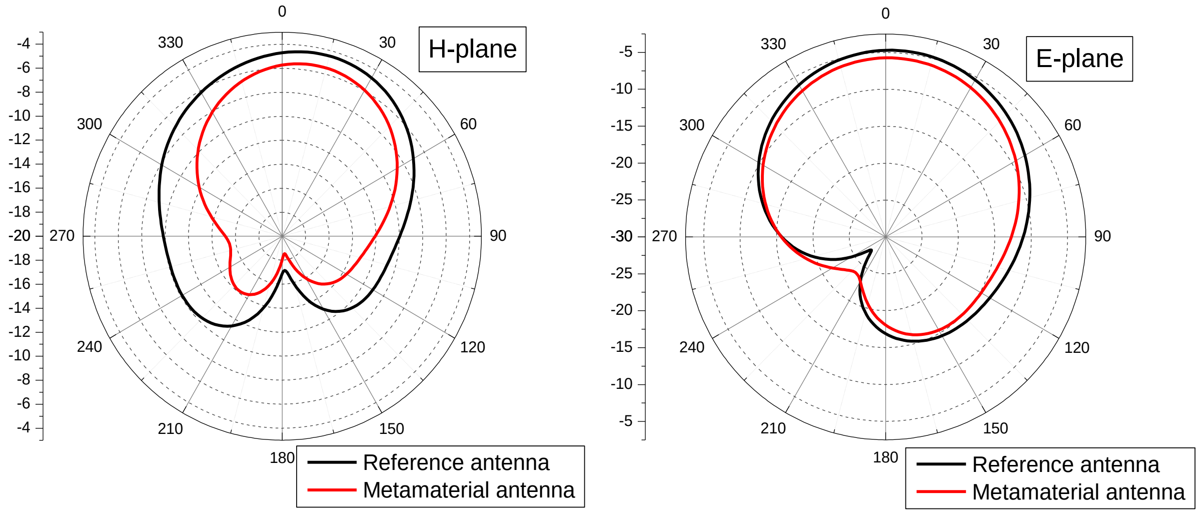
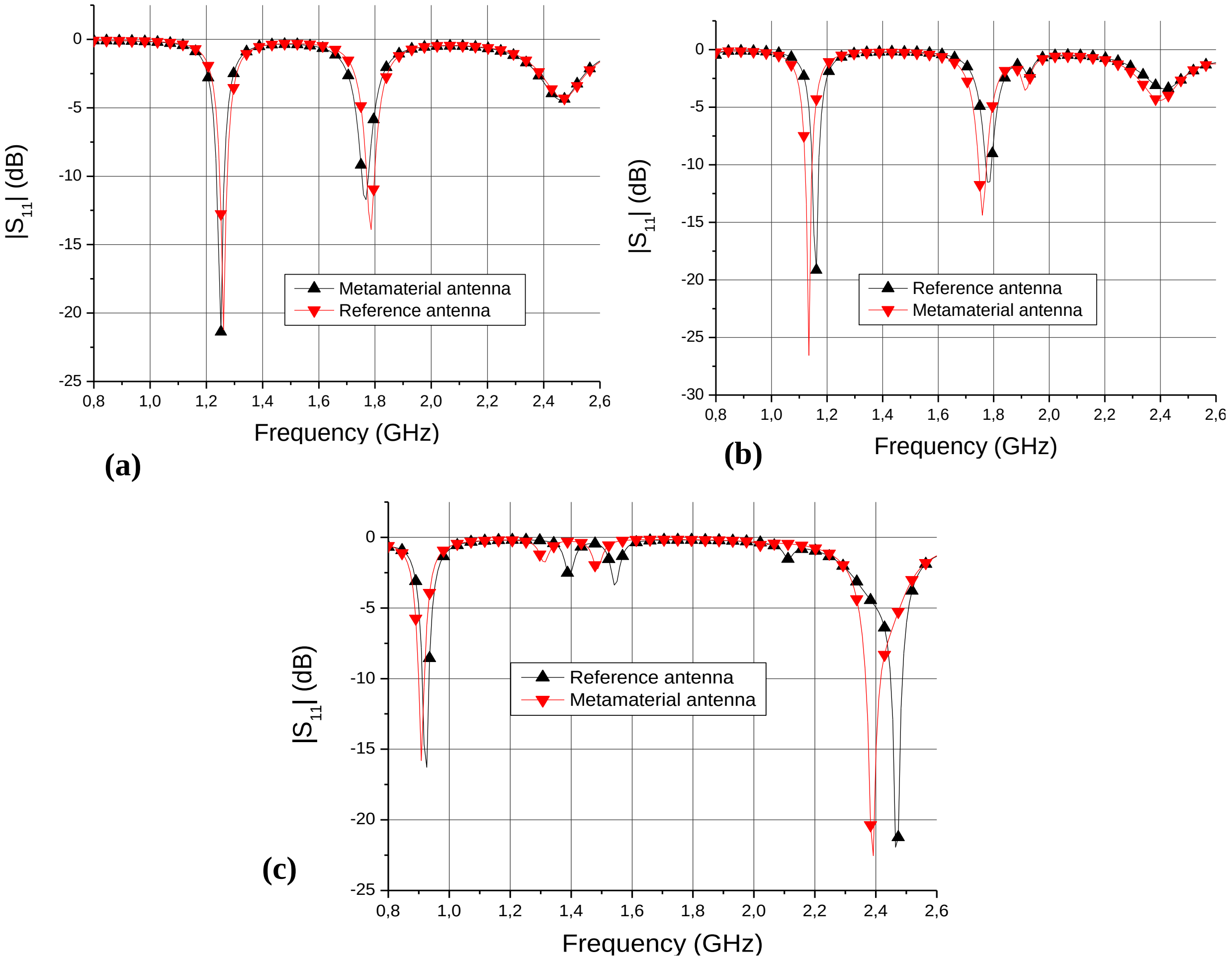


Fig IV.12: The Radiation Pattern Comparisons between the Reference antenna in the step 5 and MTM antenna at 2.4 GHz frequency.

Fig IV.10 shows the Reflection coefficients comparison between the Reference and Metamaterial antennas. Where we note that the two antennas have the same return loss -15.15 dB in the lowest frequency 0.918 GHz, while in the higher frequency band 2.4 GHz, we have a good matching comparing to the reference antenna the reflection coefficient is around of 23 dB. Wearable antennas have a low gain (see Fig IV.11 and Fig IV.12) in order to communicate efficiently without harming the human body when exposed to radio frequency (RF) energy, the appearance of the negative sign in the decibel unit is due to the value of the gain being less than one (-5.48 dB).

Because the metamaterial antenna has a complex design consists of 41 × 64 cells which makes the simulation very slow and time consuming, we simulated only three stages which show the results of comparing its reflection coefficient with the reference antenna in the figure IV.8, where showed similar results regarding the comparison between resonance frequencies and bandwidth. We call the metallic antenna a reference antenna in all the following figures.



(a) **(b)** **(c)**

Fig IV.13: The Reflection Coefficients comparison between reference and metamaterial ….antenna, **(a)** For antenna in step1, **(b)** antenna in step 2, **(c)** antenna in step 5.

Finally, we obtain an agile metamaterial antenna that can switch from one stage to another by controlling the type of unit cells.

IV.5 Conclusion

In this chapter we present a new technique in the field of antennas, which is the reconfigurability in frequency using an agile metamaterial unit cell.

Firstly, we simulate a five stages metallic antenna with each stage adding slots until we reach a dual band antenna for ISM applications. Then we emulate the metallic antenna by metamaterial antenna with the same sizes. The antenna is emulated using an agile metamaterial unit cell with controlled behavior conductive or dielectric that can switch between two types connected or disconnected depending on the state of the switching system integrated in the unit cell (ON/OFF). We replace the patch with a connected unit cell type and the slots with a disconnected unit cell type. Through the results of the comparison between the reference and metamaterial antennas we conclude a return loss equal -23 dB at 1.222 GHz, in step 2 at 1.262 GHz, but in step 5 there is a difference between the reference and metamaterial antennas where the reference antenna shifts to 2.455GHz. We achieve a wearable and reconfigurable metamaterial antenna operating in a several dual- band such as the ISM applications

Finally, the good agreement between ours simulation results and the experimental results of the reference antenna allows us to validate our metamaterial reconfigurable design.

Conclusion

Conclusion

The main objective of this dissertation is to design an agile metamaterial patch antenna with a defect and compare it to a reference antenna. In order to obtain a reconfigurable antenna operating in dual band for wearable and ISM applications.

In the first chapter, we have generally described the artificial composite materials called metamaterials.

The second chapter begins with on applications of metamaterials in design to improve antenna parameters. The metamaterials can be applied as an environment of the antenna or as part of the antenna. Among the most important metamaterial applications is achieving agility in antenna parameters such as reflection coefficient, radiation pattern, and polarization, and how to apply metamaterials in wearable antennas.

In the last chapter, we got interested by designing of unit cell controlled by an external switching system and which exhibits two different behaviors depending on the switches states (ON or OFF). When the switches are open (OFF-state), the unit cell behaves as a dielectric medium with a refractive index greater than unity, and we refer to this type of unit cell as metamaterial disconnected cross type. When the switches are closed (ON-state), the unit cell behaves as a conductive material with a refractive index near zero, and we refer to this type of unit cell as metamaterial connected cross type.

Then we simulated two antennas, a metallic and the emulated based on metamaterials with the same conditions in order to compare their results with each other. We performed five steps on each of them to obtain a dual-band antenna in the last one, where the steps consist of gradually placing slots inside the patch in specific places and sizes. The resulting antenna operating on a dual frequency band: the first one is 0.918GHz end the second is 2.4GHz, a lower resonance frequency of −17 dB, the upper resonance frequency of −23 dB with gain of -5.68 dB .The negative gain is due to the antenna is used in the medical field **ISM** band.

We mentioned that we were able to obtain an agile antenna using metamaterials that can operate at different frequencies and can switch between them by adjusting the shape of the slots (defects) within the metamaterial antenna patch part.

The simulation results obtained by the HFSS software agree well with the experimental results of the reference antenna and allow to validate our reconfigurable metamaterial design.

Bibliography

[1] H.Singh, Srivastava, S. Kumar, B.K. Kanaujia,'' A Planar Dual-Band Antenna for ISM/Wearable Applications'', springer 03 January 2021.

[2] A.A.Omar ,S.FERHAT,''High performance metamaterial based microstrip antenna'',memoire de Master, Laghouat, Juillet 2020.

[3] Angela Demetriadou, '' Studies of Metamaterial Structures ‘', Thesis of Doctor, Univ of London, January 2010.

[4] Tie Jun Cui, David R. Smith, Ruopeng Liu, “Metamaterials Theory, Design, and Applications “, Springer Science Business Media, LLC 2010.

[5] Ashwin K. Iyer, Andrea Alù, Ariel Epstein,” Metamaterials and Metasurfaces Historical Context, Recent Advances, and Future Directions”, IEEE Transaction on Antenna and Propagation, VOL. 68, NO. 3, MARCH 2020.

[6] D.B.Brito, ‘'Metamaterial Inspired Improved Antennas and Circuits'',these de doctorac Natal,RN-Brazil, December 2010.

[7] Rakhesh S. Kshetrimayum, “A brief intro to metamaterials”, IEEE Potentials, December 2004/JANUARY 2005

[8] Vikrant Thakur, Dhruva Chaudhary,'' Metamaterials: A Leading Edge of Science and Technology'', International Journal of Computer Applications (0975 – 8887) Volume 98– No.9, July 2014.

[9] K.Gangwar , Dr. Paras ,Dr. R.P.S. Gangwar,'' Metamaterials: Characteristics, Process and Applications'', Department of ECE, GBPUAT Pantnagar, Uttrakhand, India, ISSN 2231-1297, Volume 4, Number 1 (2014), pp. 97-106.

[10] Sen YAN,'' Metamaterial Design and its Applications for Antenna'',Heverlee, Belgium, May 2015.

[11] Marcio SILVA PIMENTA, ‘Antennes souples à base de métamatériaux de type conducteur magnétiques artificiels pour les standards de systèmes de géolocalisation’, doctoral thesis, NICE Novembre 2013.

[12] Boudghene Stambouli Hadjer, Bounebbab Sabiha ,“Eude et Conception d’Antennes à Résonateurs Diélectriques ‘' Thesis of Master ,Tlemcen ,2017.

[13] Yi Huang, Kevin Boyle, “Antennas from Theory to Practice”, first edition 2008.

[14] Tamanna Yeasmin Usha, Tarannum Choudhury, Hanan Ashrafi Anushka “Design of Metamaterial Loaded Microstrip Patch Antenna Array”, BRAC, Summer 2018.

Bibliography

[15] Pere Josep Ferrer Gonz´alez,’’ Multifunctional Metamaterial Designs for Antenna Applications’’,thesis of PhD, Barcelona, June 2015.

[16] W.J.Krzysztofik , C.T.Nghia , “Metamaterials in Application to Improve Antenna Parameters”, Nghe An, Vietnam, 28 February 2019.

[17] Christos G. Christodoulou “Reconfigurable Antennas for Wireless and Space Applications”, Proceedings of the IEEE | Vol. 100, No. 7, July 2012.

[18] A. H. Ramadan, K. Y. Kabalan, A. El-Hajj, S. Khoury, M. Al-Husseini, “A Reconfigurable U-koch Microstrip Antenna for Wireless Applications”, Progress In Electromagnetics Research, PIER 93, 355–367, Beirut 1107 2020, Lebanon.

[19] Boudghene Stambouli Hadjer, Bounebbab Sabiha ,“Eude et Conception d’Antennes à Résonateurs Diélectriques ‘’ Thesis of Master ,Tlemcen ,2017.

[20] Behnam Zarghooni,” Reconfigurable Metamaterial-based Antenna Using a Novel class of Miniaturized Agile Unit-cells”, Thesis of Doctor, Québec, August 2015.

[21] K.BOURAS,.A.LABIAD,C.SALEH,.BOUZOUAD,’’ Emulation of metamatrial waveguides’’, Algerian journal of signals and systems (AJSS), september 2018.