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Frequency Agile- Metamaterials based microstrip antenna

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Dedication

To the one who give me life, love, courage, to you dear mother, my love and my gratitude, I wish you rejoice with the right now, the most beautiful smile that I see in the universe "my mother Amina"

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AMel

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All words cannot express gratitude, love,

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To the whole family

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To all the friends and colleagues from near and far who brought me their requests to accomplish this work.

Ahlem

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Listed of abbreviations

AMC	**A**rtificial **M**agnetic **C**onductive
c	The speed of light in the vacuum
CPW	**C**ommercial **P**rocessing **W**orkload
DC	**D**irect **C**urrent
DPS	**D**ouble **P**ositive
EBG	**E**lectromagnetic **B**and
FET	**F**ield **E**ffect **T**ransits
FSS	**F**requency **S**elective **S**urface
g	Gap
h	Height
HIS	**H**igh **I**mpedance **S**urface
ISM	Standard of **I**ndustrial, **S**cience and **M**edical
l	Length
LCP	**L**iquid **C**rystal **P**olymer
LHM	**L**eft- **H**ands **M**edium
MEMS	**M**icro **E**lectro **M**echanical **S**ystem
MESFET	**M**etal **E**ffect **T**ransits
MIMO	**M**ultiple **I**mpute **M**ultiple **O**utput
MMIC	**M**onolithic **M**icrowave **I**ntegrated **C**ircuit
MNG	Mu-Negative Metamatreials
NIM	**N**egative **I**ndex **M**etamaterials
OFDM	**O**rthogonal **F**requency **D**ivision **M**ultiplexing
PC	**P**hotonic **C**rystal
PCB	**P**rinted-**C**ircuit-**B**oard
Pin diode	**P**ositive **I**ntrinsic **N**egative diode
RF	**R**adio **F**requency
RHM	**R**ight-**H**anded **M**edium
S_{11}	Coefficient of reflexion
SDR	**S**oft **D**efined **R**adio
SSR	**S**lip **R**ing **R**esonators
UWB	**U**ltra-**W**ide Band
VSWR	**V**oltage **S**tanding
w	Width
WIFI	**Wi**rless **Fi**delity
n	The refractive index
ε	Permittivity
μ	Permeability

General Introduction

In ancient times, voice was the only method of communication between humans. When the need of slightly distant communication arises, many conventional devices like drums, and then visual methods like flags and smoke signals were used. These visual devices, of course, utilized the optical range of the electromagnetic spectrum but the use of electromagnetic spectrum outside the visible region like radio waves and microwaves has been very recent in human history. Electromagnetic spectrum is one of the greatest natural resources available for mankind and to harness this resource antenna is a primary element. Multiple antenna structures have been developed for many applications ranging from radar to space communications. Recently, printed antennas like microstrip patch antenna have been widely used due to its integration property. Every antenna design has some inherent limitations associated with it. In recent times, artificially designed structures like metamaterials and electromagnetic bandgap structures have been widely used to overcome many inherent limitations of these antennas. Unlike other methods, this new method utilizes the inherent properties of these artificially designed materials to enhance microstrip antenna performance.

The resonant elements that grant metamaterials their unique properties have the fundamental limitation of restricting their useable frequency bandwidth. The development of frequency-agile metamaterials has helped to alleviate these bandwidth restrictions by allowing real-time tuning of the metamaterial frequency response. We study in this dissertation the effect of add cells metamaterials types cross in antenna patch travel at 22GHz and we see the agility in frequency of this antenna based metamaterials

The ability of metamaterials to create electromagnetic responses absent in nature has initiated the new research field of antenna which has applications agility of Frequency, agility of bandwidth. Frequency-agile metamaterials, which allow antenna to adjust the electromagnetic response in real time, are emerging as an important part of this field.

The hybrid-metamaterial approach wherein natural materials are integrated into the metamaterial composite has been particularly successful in enabling frequency-agile metamaterials.

For this the study focused on the use of HFSS software (simulation and professional modeling tool) with the help of MATLAB which by its ease of simulation, allowed us interpret well and belter explained the results.

The dissertation is organized as follows.

The first chapter of this dissertation is devoted to the state of the art of theoretical concepts of metamaterials.

The second chapter will give an overview of microstrip antenna, then the concept of agile antennas will defined by expose there classification and various techniques allowing realizing the agility.

The last chapter is divided into three parts. Firstly; characteristic of the type cross metamaterial elementary unit cell, secondly; the design of the patch antenna working frequency at 22GHz, finally the study of antenna frequency agility.

Chapter I

State of art

I.1 Introduction

Science and technology have an insatiable thirst for better and more materials that can promise unlimited prospects. In the domain of optics, a newcomer has been talked about a lot: the "metamaterial". Metamaterials are artificial materials that have properties singular electromagnetic that we don’t find in nature or in their constituents taken separately. The most interesting feature is the possibility of control or modify the permittivity and permeability of the material to obtain a behavior adapted to a specific application. 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. This first chapter draws up a theoretical reminder in the form of a general study of metamaterials, starting with a brief history of periodic structures, then we present their definitions, its classifications, its fundamental characteristics such than negative permeability and permittivity. Finally we will mention the potentials applications such as perfect lenses, invisibility cloak, and the field of antennas

I.2 Historical points for Metamaterials

In 1898 J.C. Bose showed the possibility of existence of artificial material by conducting microwave experiment on twisted structure. Later, the physicist victor Veselgo(1968) presented theoretical investigation and Pendry et. al in 1996 used an artificial wired medium whose permittivity is negative to realize artificial electric plasma, followed by this, in 1999 magnetic plasma is realized whose permeability is negative using split-ring resonators (SRR).Smith et al(2004) had realized gradient refractive index medium to bend electromagnetic waves. Metamaterial opened up a new exciting world for the scholars. The concept of negative refractive index is now widely accepted and focus of the research has moved toward applications. The word was first coined by Rodger M. Walser (2001) who gave the following definition “Metamaterials are defined as macroscopic composites having a man-made, three dimensional, periodic cellular architecture designed to produce an optimized combination, not available in nature, of two or more responses to a specific excitation.”

“Metamaterials are artificial periodic structures with lattice constants that are much smaller than the wavelength of the incident radiation. Therefor providing negative refractive index characteristics”. [1]

I.3 Definition of metamaterials

Matter is constituted of atoms and molecules see (Figure I.1), and is seen by the electromagnetic waves as electric and magnetic dipolar distributions, which are the microscopic sources of the polarization and magnetization phenomenon. Generally, we can cite three microscopic mechanisms of polarization. The first one is the electronic polarization. It is related to the modification of the internal charges repartition of each atom or ion. It is constantly present whatever the state of the considered material. The second one is the atomic or ionic polarization. It concerns the displacements of atoms or ions compared to their equilibrium positions in the crystalline edifice where they belong. The third one is the orientation polarization. It arises when the atomic or molecular dipole moments are oriented under an electric field action. The origin of the microscopic magnetization is the magnetic moments of the microscopic current loops resulting from the motion and spin of the charged particles present in atoms.

Metamaterials are man-made materials, composed of artificially structured unit cells that are designed of conventional materials and usually (but not necessarily) arranged in periodic fashion [2] .Inclusions, like metal thin wires or split ring resonators (SRR), behave

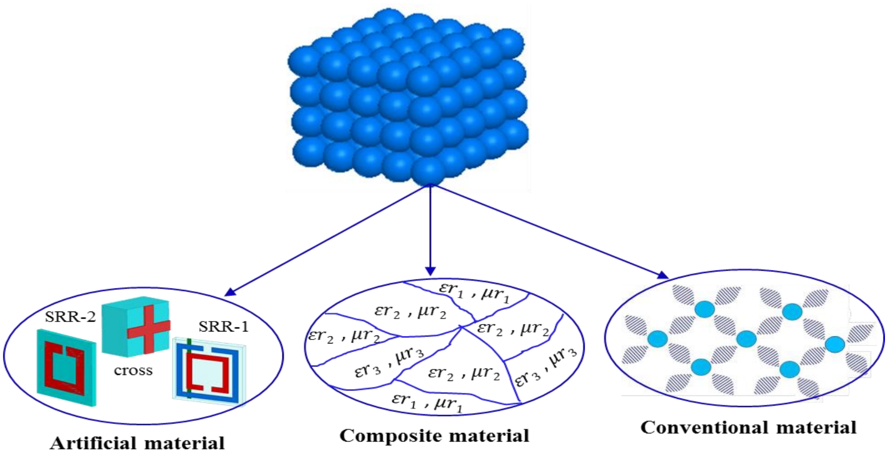


Figure I. 1: Unit cell types arranged in space compared to atomic scale in conventional materials**.**

I.4 The properties of metamaterials

The electromagnetic property of these metamaterials can be described by the Maxwell's equations. The transformation of this equation serves to highlight the properties of metamaterials. They are given in the set of equations:

$$\nabla \times \vec{E} = -j\omega\,\mu\,\vec{H} \tag{I.1}$$

$$\nabla \times \vec{H} = -j\omega\,\varepsilon\,\vec{E} \tag{I.2}$$

Where $\vec{E}$ and $\vec{H}$ are the vectors of electric and magnetic fields strengths, respectively; ε and μ are the material permittivity and permeability; ω is an angular frequency $j = \sqrt{-1}$ is an imaginary number.

In the case of the plane wave propagation, the electric and magnetic fields are represented as:

$$E = E_0\, e^{(-jkr+jwt)} \tag{I.3}$$

$$\mathrm{H} = \mathrm{H_0}\, \mathrm{e}^{(-\mathrm{jkr}+\mathrm{jwt})} \tag{I.4}$$

In addition, to evaluate the properties of materials, a general definition of the Poynting power density vector $\vec{S}$is mentioned, which is subdivided into the time $e^{+jwt}$and the space e^{-jwt} components. The real part of the Poynting vector, which determines the energy flow, is represented by the following formula:

$$\vec{S} = \frac{1}{2}\,\vec{E} \times \vec{H} \tag{I.5}$$

For the plane wave, the electric field $\vec{E}$ and the magnetic field $\vec{H}$ are defined by

$$\vec{E} \times \vec{H} = j\omega\,\mu\,\vec{H} \tag{I.6}$$

$$\vec{K} \times \vec{H} = -\omega\ \varepsilon\,\vec{E} \tag{I.7}$$

In the isotropic and homogeneous medium, the values of ε and μ are simultaneously positive. In this medium , the electric field $\vec{E}$, magnetic field $\vec{H}$, and propagation vector $\vec{K}$ form the right circulate triad of orthogonal vectors. Therefore, it is also defined as the right-handed medium (RHM), where the $\vec{S}$, $\vec{K}$ have the same directions and electromagnetic waves can propagate in them [3].

In that case, the values of ε and μ are negative simultaneously; so, Eqs (I.6) and (I.7) can be rewritten as:

$$\vec{\mathrm{K}} \times \vec{E} = -\,\omega\,|\mu|\,\vec{H} \tag{I.8}$$

$$\vec{K} \times \vec{E} = j\omega|\varepsilon|\,\vec{E} \tag{I.9}$$

In this case, the electric field $\vec{E}$, the magnetic field $\vec{H}$, and the propagation vector $\vec{K}$ form left-hand circulate triad of orthogonal vectors, which also is defined as the left-hand medium (LHM). In this medium, the Poynting vector $\vec{S}$ has the opposite direction to the propagation vector $\vec{K}$, so that it can support backward waves, i.e., the energy and wave fronts travel in opposite directions. Figure I.2 depicts triplet models for RHM (a) and LHM (b) materials.

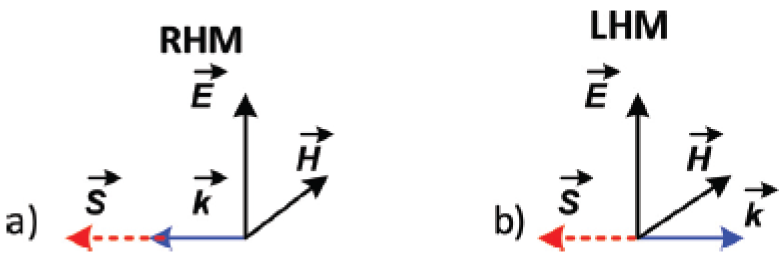


Figure I. 2: The vectors $\vec{E}, \vec{H}$, k form the trio for right-handed (a) and left-handed media (b)

I.5 Metamaterial characteristics

The metamaterial classification was first proposed by Veselago scientists by considering the permittivity, ε, and the permeability, μ of a homogeneous material. As a result, when ε and μ are simultaneously negative, some abnormal physical phenomena occur such as the reversal of the Snell Law, the reversal of Cerenkov Effect, the reversal of the Doppler Shift. The relationship between the refractive index and the constituent parameters ε and μ is given by the formula:

$$n = \pm\sqrt{\varepsilon_r\,\mu_r} \tag{I.10}$$

Where ε_r and μ_r are the relative permittivity and permeability of the material, related to the free space permittivity and permeability by: $\varepsilon_r = {}^{\varepsilon}/_{\varepsilon_r} = 8.854 \times 10^{12}\ {}^{F}/_{m}$ and $\mu_r = {}^{\mu}/_{\mu} = 4 \times \pi \times 10^{-7}\ {}^{H}/_{m}$, respectively.

From Eq. (10), sign $\pm$ of n can get 1 in the four cases, which depends on the pairs of sig of ε_r and μ_r. The electromagnetic metamaterials are classified based on each case of the pair sign ε and μ, they are shown in Figure I.3. With each region corresponding to the structure created different metamaterials.

In the quadrant I, both parameters ε and μ are positive, and are called Double Positive (DPS) or right-handed medium (RHM). These materials can be found in nature, such as dielectric materials, in which the electromagnetic waves can propagate.

In the quadrant II, the parameters are ε < 0 -negative, and μ > 0 +positive, and such material is called as epsilon negative (ENG) medium, and is represented by a plasma.

In the quadrant III, parameters ε < 0 - negative, and μ < 0 -negative, this region is called double-negative (DNG) or left-handed medium (LHM), and such material could not be find in nature.

The quadrant IV ε > 0 +positive, and μ < 0 -negative, and such material is called μ—negative (MNG), represented by ferrite materials. Such medium has below plasma frequency. Most waves can propagate in two mediums, namely: at region I and III. Non-propagating evanescent waves are found in regions II and IV [4].

Currently, two basic types of structures are being used for designing the most metamaterials: a dense array of thin wires (the electrical dipoles) and an array of split-ring resonators (SRRs) (the magnetic loops).

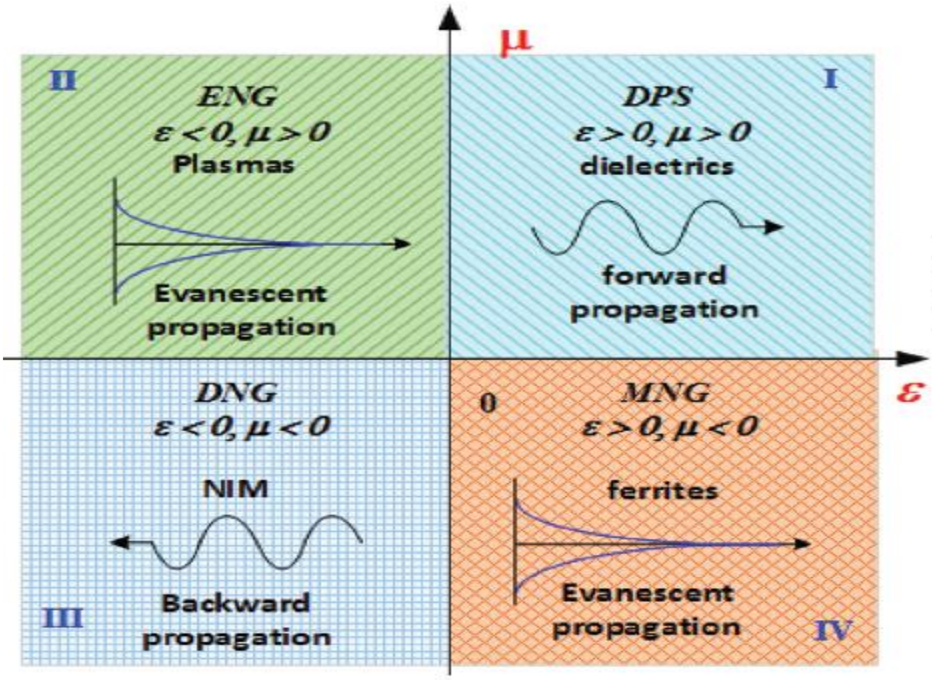


Figure I. 3 : The classification of electromagnetic MTMs based on signs of the ε and μ.

I.5.1 The epsilon-negative (ENG) metamaterial

The ENG metamaterial uses the metallic mesh of thin wires, for obtaining negative value of ε. These parallel metal wires, which exhibit high-pass behavior for an incoming plane wave, whose electric field is parallel to the wires[5] .The cylindrical array displays the negative permittivity below the plasma frequency, the wire can be made of copper, aluminum, silver, or gold, they are arranged periodically as shown in (Figure I.4) (a). The effective permittivity is given by the equation [6]:

$$\varepsilon_p = 1 - \frac{\omega_p^2}{\omega^2} \quad (I.11)$$

Where ω is the frequency of the propagating electromagnetic wave and ω_p is the plasma frequency.

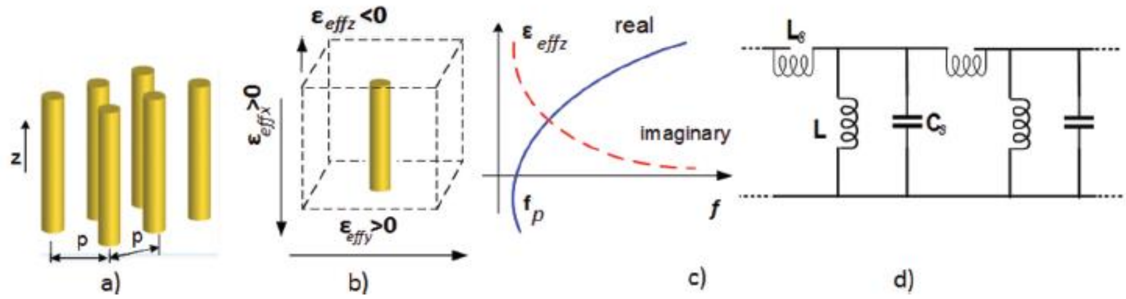


Figure I. 4: An array of thin conducting wires (a), unit cell (b), plots of the effective permittivity of an array of wires (c), and its equivalent circuit (d).

From Equation (I.11), it is shown that when the propagation frequency is below the plasma frequency, its permittivity is negative [7]. This behavior is similar to the propagation of the electromagnetic waves in plasma medium. The propagation frequency as close to the plasma frequency, the value of effective permittivity is increasing. At the plasma frequency, the effective permittivity is equal to zero, and this corresponds to the refractive index equal to zero [8].

Below the cutoff frequency of the array, there is no wave propagation, and the electromagnetic waves are totally reflected waves. This behavior is similar to the propagation of electromagnetic waves in the plasma medium. The plasma frequency depends on the lattice constant p and the radius of the individual wire. If the lattice constant frequency is several times smaller than the wavelength, the wire array can be considered as an equivalent of the continuous plasma [9].

I.5.2 The mu-negative (MNG) metamaterial

As the mu-negative (MNG) material, the most popular structure has been using is split ring resonators (SRRs). A unit cell of the SRR is composed of two concentric metallic rings (can be circle or square) and separated by a gap d (see Figure I.4 (b)) Each ring has a narrow slot, and they are spaced 180 degree apart on each side. The gap between inner and outer ring acts as a capacitor, while the rings themselves act as an inductors. Therefore, the combination of the two rings acts as an LC resonance circuit. The effective permeability of MNG metamaterials is given by the formula (I.12):

$$\mu_{eff=} \mu'_{eff} - \mu'_{eff} = 1 - \frac{f_{mp}^2 - f_0^2}{f^2 - f_0^2 - j\gamma f} \qquad (I.12)$$

Where f is the frequency of the signal, f_{mp} denotes the frequency at which (in the lossless case) $\mu_{eff} = 0$ ("magnetic plasma frequency"), f_0 is the frequency at which μ_{eff} diverges (the resonant frequency of the SRR), and γ represents the losses. The frequencies fmp and f0 depend on the lattice constant (p), and the geometry parameters of the SRR such as inner and outer radii of the rings, the width of the gap between the rings, and the slit width [10]. The dependence of μ_{eff} on the frequency is shown in Figure 4c.

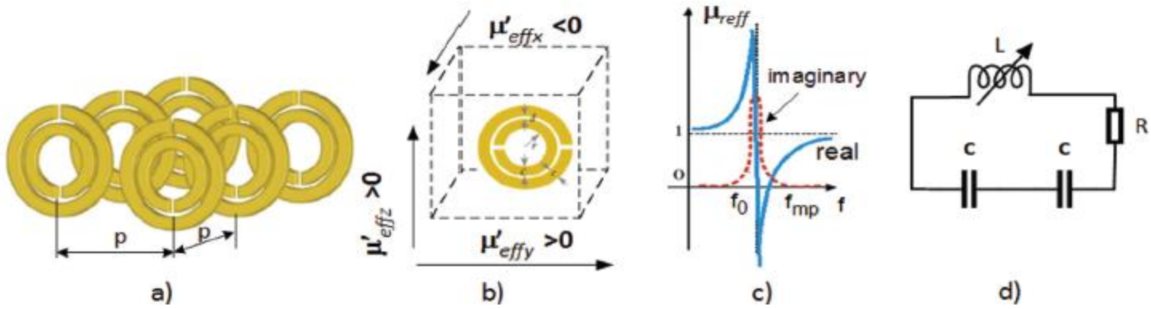


Figure I. 5: An array of SRRs (a), SRR unit cell (b), the effective permeability of SRR array (c), and equivalent circuit (d).

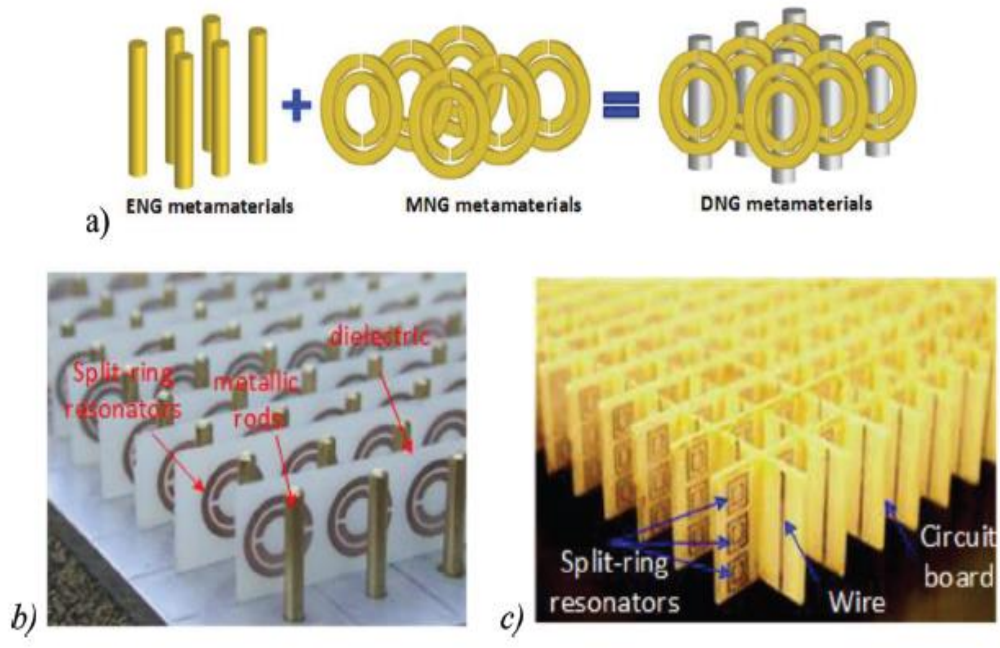


Figure I. 6: Combination of thin wires and SRR to form DNG metamaterials (a) and examples of realizations of DNG metamaterials (b) and (c)

I.5.3 The double-negative (DNG) metamaterial

The DNG metamaterial is also known as the negative refractive index material (NIM). The properties of the metamaterials DNG were first achieved by combining the thin wire-based ENG structure with SRR-based MNG structure (Figure I. 5a) [11]. This combination satisfies the requirement of $\varepsilon < 0$ from a wire/rodded medium (as an artificial dielectric) and $\mu < 0$ from a split ring resonator (SRR). The first structure was constructed from the combination of planar SRRs etched on a thin dielectric layer and metallic rods (Figure I.5b). In addition, to take advantage of the two sides of the dielectric layers, two-dimensional metamaterials have been designed by engraving the SRR on one side of the dielectric layer and planar strips on the other [12] (Figure I. 5c). Because of DNG is made up of thin wire medium and SRRs medium, which their strong resonance behavior (Drude-Lorentz models) affects the frequency. Therefore, the generated DNG metamaterials are also dependent on frequency, which results in the refractive index n being reformatted as:

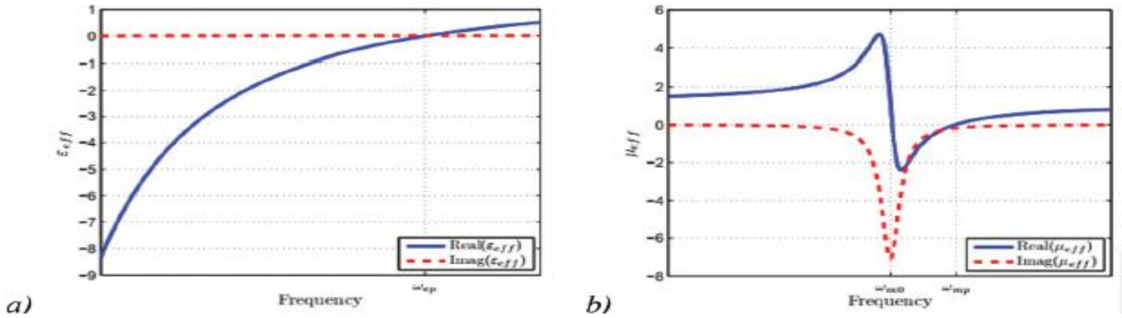


Figure I. 7: The plots of effective permittivity (a) and permeability (b) of the DNG metamaterial**.**

$$n \equiv n_{eff}(\omega) = \sqrt{\varepsilon_{eff}(\omega)\,\mu_{eff}(\omega)} \qquad \text{(I.13)}$$

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

These effective material parameters are characterized by their Drude-Lorentz dispersion models and have the form described in Eqs. (14) and (15)

$$\epsilon_{eff}(\omega) = 1 - \frac{\omega_{ep}^2 - \omega_{e0}^2}{\omega^2 - \omega_{e0}^2 + j\omega\gamma_c} \qquad \text{(I.14)}$$

$$\mu_{eff}(\omega) = 1 - \frac{F\omega^2}{\omega^2 - \omega_{m0}^2 + j\omega\,\Gamma} \qquad \text{(I.15)}$$

Where ω_{ep} and ω_{mp} are the electric and magnetic plasma frequencies, respectively, ω_{0p} and ω_{e0} are the electric and magnetic resonant frequencies, respectively, γ_c is the collision frequency, F is an amplitude factor, and Γ is a damping factor. These expressions have been plotted in Figure I.6. To get the DNG metamaterial from the combination of the ENG and MNG structures, both negative regions of them must coincide. Then, the ENG domain is found corresponding to $\omega_{e0} < \omega < \omega_{0p}$ and the MNG region corresponding to $\omega_{m0} < \omega < \omega_{mp}$. Note that, if the wires are electrically continuous, their resonant frequency is 0 ($\omega_{e0} \approx 0$). This leads to results, since the ENG region is wider compared to the MNG region, the magnetic resonator metamaterial limits the DNG performance, when assembled together with an electric resonator metamaterial.[12]

I.6 Types of metamaterial

a. Electromagnetic Metamaterials

Electromagnetic metamaterials (EM) are the materials which have a new sub section within electromagnetism and physics. EM is used for optical and microwave applications like, band-pass filters, lenses, microwave couplers, beam steerers, and antenna radomes.

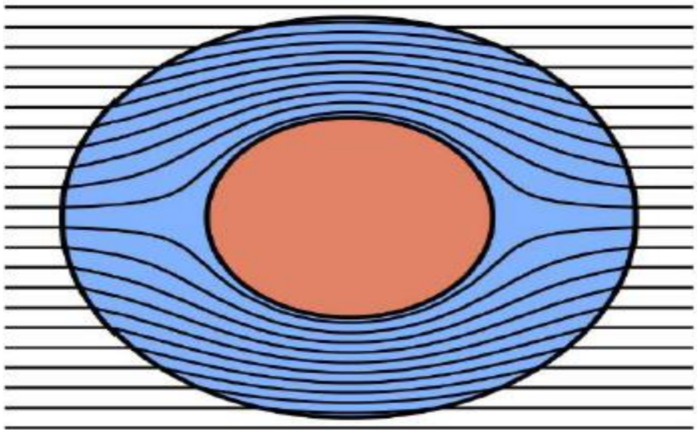


Figure I. 8: Electromagnetic metamaterials

A metamaterials affects lesser on electromagnetic waves as compared to wavelength of electromagnetic radiation**.**

❖ **Single Negative Metamaterials:** Single negative metamaterials (SNG) have either negative permittivity or negative permeability. The combination of two SNG layers into one creates another form of DNG metamaterials. To conduct wave reflection experiments, the slab of MNG materials and ENG materials have been joined. Like DNG metamaterials, SNGs change their parameters like refraction index n, permittivity ε and permeability μ, with change in frequency due to their dispersive nature. [13]

❖ **Double Negative Metamaterials:** Double negative metamaterials (DNG) are the metamaterials that have both permittivity and permeability is negative with negative index of refraction. These are also known as negative index metamaterials (NIM) .Other names for DNGs are left handed media, media with a negative refractive index, and "backward-wave media [14].

❖ **Electromagnetic Band Gap (EBG) Metamaterials:** Electromagnetic band gap metamaterials control the propagation of light. It is achieved either by photonic crystals (PC), or left-handed materials (LHM). Both classes have artificial structure that control and manipulate the propagation of electromagnetic waves. [15]

❖ **Bi-isotropic and Bi-anisotropic Metamaterials:** Based on the independent electric and magnetic responses described by the parameters permittivity and magnetic permeability, the metamaterials are categorized into single or double negative. However in many examples of electromagnetic metamaterials, the electric field causes magnetic polarization, and the magnetic field induces an electrical polarization, i.e., magneto electric coupling. Such media denoted as bi-isotropic media because it exhibits magneto-electric coupling that is anisotropic, and also called as bi-anisotropic. [15]

b. Chiral Metamaterials

Chiral metamaterials consist of arrays of dielectric gammadions or planar metallic on a substrate. When a linearly polarized light is incident on the array, it becomes elliptically polarized upon interaction with the gammadions with the same handedness as the gammadion itself [16].

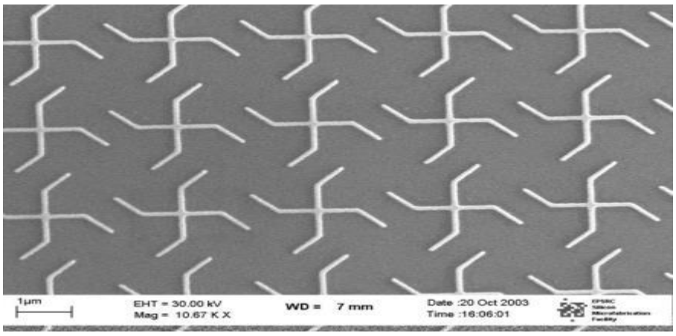


Figure I. 9: Chiral metamaterials

c. Terahertz Metamaterials

Terahertz metamaterials are the combination of artificial materials that interact at terahertz (THz) frequencies and still under development. With negative values of permeability these metamaterials can achieve a desired magnetic response is called passive materials. Because of this, "tuning" is achieved by fabricating a new material with slightly altered dimensions to create a new response. Terahertz waves lie just before the start of the microwave band to far end of the infra-red band.

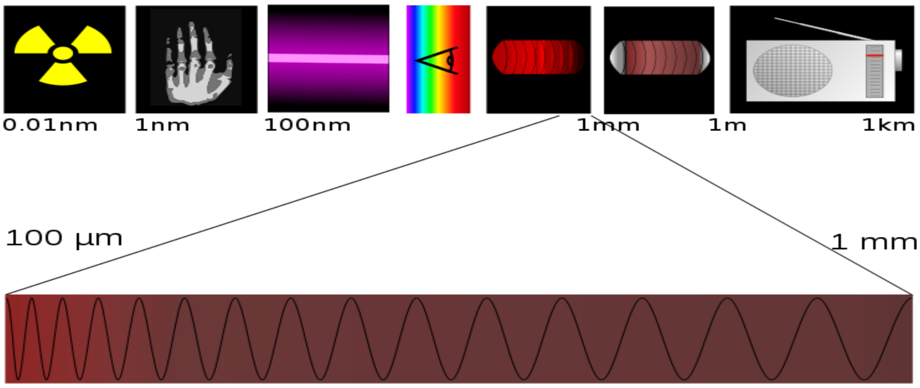


Figure I. 10: Wave formation of Terahertz metamaterials

The range of terahertz metamaterials frequency is 0.1 to 10 THz for research or other applications.

d. Photonic Metamaterials

Photonic metamaterials are the type of electromagnetic metamaterials that designed to interact with optical frequencies is known as Optical metamaterials. Photonic metamaterials radiates the source at optical wavelengths . Furthermore, the sub wavelength period differentiates the photonic metamaterials from photonic band gap structure. This is because the optical properties do not arise from photonic band gaps, rather from a sub wavelength interaction with the light spectrum. The metamaterials with the capability of zero index of refraction (ZIMs) and negative values for index of refraction (NIMs) is the active area of research in optical materials [17].

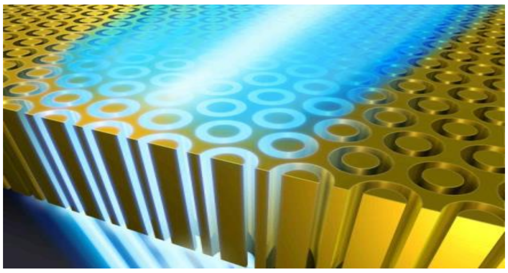


Figure I. 11: Photonic Metamaterials

e. Tunable Metamaterials

These are the metamaterials that has the ability to randomly change the frequency of a refractive index. An incident electromagnetic wave gives variable response with these metamaterials. This includes how an incident electromagnetic wave interacts with a metamaterials in remote controlling. The structure of the tunable metamaterials is changeable in real time that makes it possible to reconfigure a device during operation . Tuning in the near infrared range is achieved by varying the permittivity of nematic liquid crystal. The metamaterials can be tuned from negative index values, to zero index or positive index values. In addition, negative index values can be increased or decreased [18].

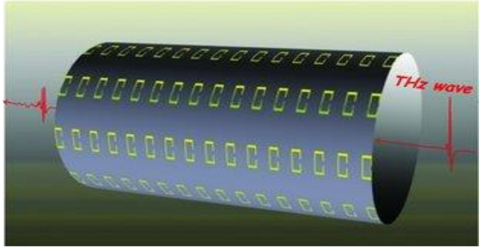


Figure I. 12: Tunable Metamaterials

f. Frequency Selective Surface (FSS) based Metamaterials

FSS based metamaterials are the substitute to the fixed frequency metamaterials with static geometry and spacing in the unit cells used to find out the frequency response of a given metamaterials. FSS based metamaterials have option to change the frequencies in a single medium but in fixed frequency response it is impossible. It was first developed to control the transmission and reflection characteristics of an incident radiation wave. FSS with specific geometrical shapes can be made-up as periodic arrays with elements of two dimensional planar. FSS based metamaterials has the interchangeable terminology of High Impedance Surface (HIS) or Artificial Magnetic Conductor (AMC). The HIS or AMC has an artificial metallic ele ctromagnetic structure. The designed structures with selection of supporting surface wave currents are different from conservative metallic conductors [18].

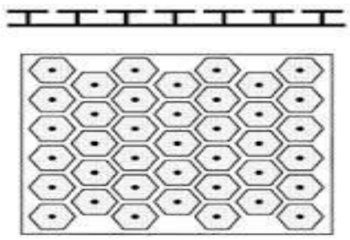


Figure I. 13: Structure of FSS

g. Nonlinear metamaterials

Are artificial materials in which the nonlinearity exists. This is due to less macroscopic electric field of the electromagnetic source than the microscopic electric field of the inclusions. The material’s permeability and permittivity describes the response of electromagnetic radiation. It may also be fabricated with some type of nonlinear metamaterials that have properties to change the power of incident wave [18].

I.7 Metamaterial applications

I.7.1 Metamaterial as Absorber

The first Metamaterial based absorber by landy (2008) utilizes three layers, two metallic layers and dielectric and shows a simulated absorptivity of 99% at 11.48 GHz as shown in (Figure I.14). Experimentally, landy was able toachieve an absorptivity of 88% .The difference between simulated and measured results were due to fabrication errors[19].

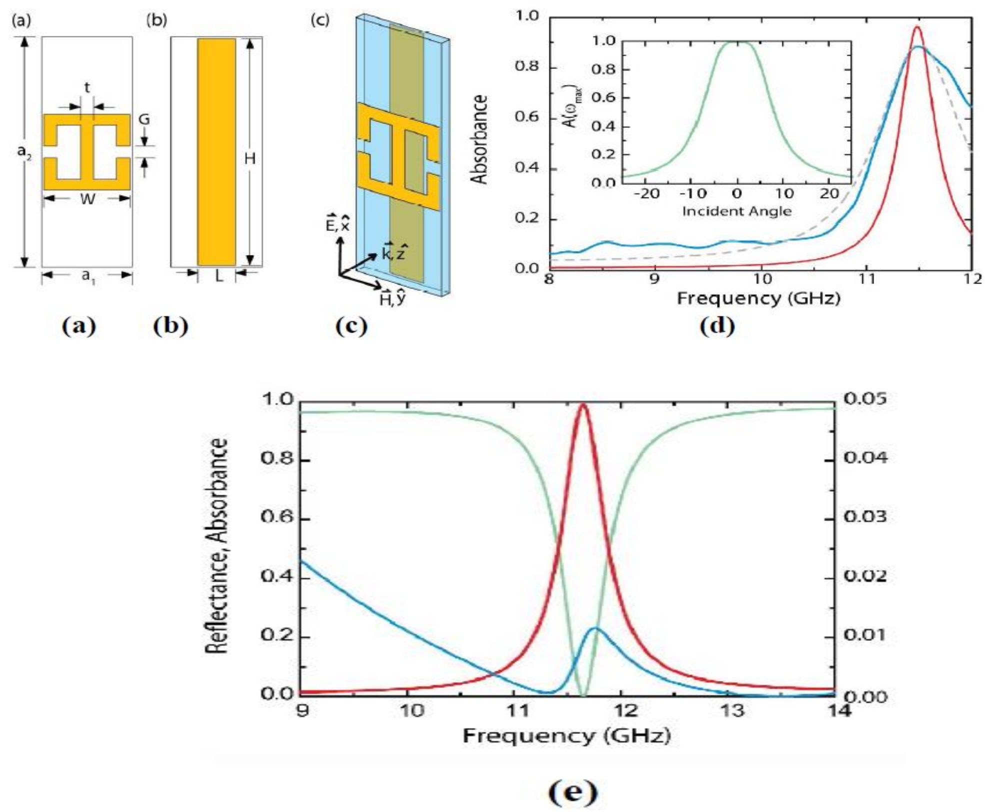


Figure I. 14: (a), (b) &(c) The unit cell is shown with its component (d) Results after fabrication (e) Results after simulation.

I.7.2 Metamaterial as superlens

Superlens uses metamaterials to go beyond the diffraction limit. Ramakrishna (2005).showed, it has resolution capabilities that go beyond ordinary microscopes. Conventional optical materials suffer a diffraction limit because only the propagating components are transmitted from a light source. The non-propagating components, the evanescent waves, are not transmitted. One way to improve the resolution is to increase the refractive index but it is limited by the availability of high-index materials.

The road to the super lens is its aptitude to significantly enhance and recover the evanescent waves that carry information at very small scales. No lens is yet able to completely reconstitute all the evanescent waves emitted by an object. So the future challenge is to design a superlens which can constitute all evanescent waves to get perfect image.[20]

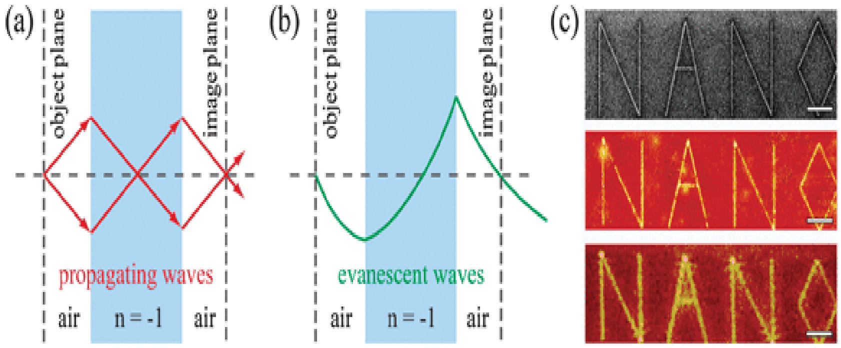


Figure I. 15: (a) Recovering of propagating waves (b) Amplification of Evanescent wave

I.7.3 Metamaterial as cloaks

Cloaking can be achieved by cancellation of the electric and magnetic field generated by an object or by guiding the electromagnet wave around the object. Guiding the wave means transforming the coordinate system in such a way that inside the hollow cloak electromagnetic field will be zero this makes the region inside the shell disappear. Metamaterial cloak based on the concept of coordinate transformation is described by Adnan noor (2010) [21].

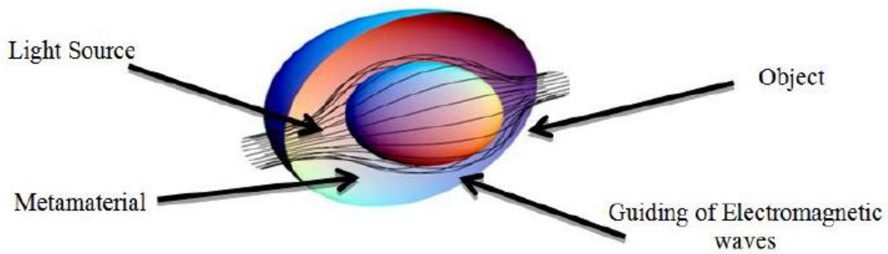


Figure I. 16: Cloaking

I.7.4 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). [22]

Figure I. 17: Metamaterial unit cells that are used for the sensor (a) Multiple SRR (b) Sierpinski SRR(c) Spiral Resonator

I.7.5 Metamaterial as Phase compensator

Metamaterial act as a phase compensator, when wave passes through a (double positive) DPS slab having positive phase shift while DNG slab has opposite phase shift so when wave exit from a DNG slab the total phase difference is equal to zero. The concept is described by Adnan Noor (2010)[21].

I.7.6 Metamaterial for Antennas application

In the antenna field metamaterials antennas are used to improve the antenna performances such as enhancing the gain, directivity and bandwidth. steering the radiation pattern and introducing agility. Materials with negative magnetic permeability could possibly allow for properties such as an electrically small antenna size, metamaterial based antennas can demonstrate improved efficiency and high bandwidth performance.

Agility means performing several functions through a device or circuit. Some time it is called also tuning or reconfiguration, depending on how the desired function is changed .

Agile antennas can be classified into three categories:

i) Frequency agile antennas, for which we can modify the antenna operating frequency.

ii) Radiation pattern agile antennas, for which we can change their radiation pattern characteristics (pointing direction, main lobe beamwidth, etc.).

iii) Polarization agile antenna, for which we can change the polarization [23].

I.8 Metamaterials advantages

- **Directivity Enhancement**

Metamaterials has inherent property that controls the direction of electromagnetic radiation in order to collect the originating energy in a small angular domain around the normal to the surface. A DNG material enhances the directive properties of an antenna. [24]

- **Bandwidth Enhancement**

Metamaterials antenna increase achieved bandwidth as compared to the conventional patch antenna .This is achieved by use of superstrate of metamaterials over conventional antenna or by loading of LHM. [25]

- **Radiated Power Enhancement**

A small antenna can increase the radiated power through the application of DNG metamaterials. A small dipole antenna enclosed with DNG metamaterials is use to increase the radiated power much more as compared to the conventional antenna. [26]

- **Beamwidth and side lobes**

The metamaterials antennas decrease the beam width and side lobe ratio and thus enhance the directivity and reduce the return loss of antenna [27].

I.9 Disadvantages of metamaterials

- Difficult to manufacture in large quantities
- It works for limited range of wavelengths
- Shape of the antenna can't be changed during operation, they are lossy. [2]

I.10 Conclusion

The work exposed in this chapter is included first of all of a history on the left media NIMs and the negative refraction after we discuss the fundamental properties of the propagation in the presence of LHMs, then the inversion in the basic phenomena of system optics is summarized, namely, Snell's law, the Doppler and Cerenkov effect, in addition the change of the geometric optical system and the concept of the perfect objective presented. Finally we cite some applications on metamaterials.

Chapter II

Overview of antennas and the agility techniques

II.1 Introduction

The concept of reconfigurable antennas (or even agile antennas) is not new, since many years. The first developments date back to the late 1960s. However, the development of antenna diversity techniques has aroused considerable and growing interest in intelligent antennas, and has largely contributed to the design of new reconfigurable antenna devices in order to make faced with the increase in the number of users, the requested functionalities and the transmission rate. The antennas designed should be able to modify their operating frequencies, bandwidths, polarizations and radiation patterns independently to adapt to changes in their environment, their context of use and to optimize their performance. Many applications continually require antennas with more functionality than conventional designs allow; we can cite as an example, communication systems, Radar systems, satellite communications, drones.

In addition, a single agile antenna can replace a number of single function antennas. The overall size, cost and complexity of a system must be reduced while improving the overall performance of the radio system. However, the development of these antennas poses very important challenges. These challenges lie not only in obtaining the desired levels of antenna functionality, but also in integrating these functionalities into complete systems to arrive at an efficient and low-cost solution. The polarization circuits of the active elements can also constitute a strong constraint by their consumption and the losses which they introduce. There are also problems related to the non-linearity of the components but also to the cost of these components.

In this chapter we will first provide a brief overview of microstrip antenna (basic parameters, feeding techniques, advantages and disadvantages...) then we will define the concept of agile antennas by expose there classification and various techniques allowing realizing the agility.

Finally, we will compare the available solutions by highlighting the advantages and disadvantages of each method to obtain the agility of the system. The different means are compared on a few main criteria: the agility of the structure, the quality factor, the power consumption, the control voltage, and the response time of the system and an evaluation of the cost of production.

II.2 Overview of antennas

An antenna is a device that is used to convert guided electromagnetic waves into electrical signals and vice versa (i.e. either in transmitting mode or in receiving mode of operation). Antennas are frequency dependent devices. Each antenna is designed for a certain frequency band and outside of this band, antenna rejects the signal. Therefore we can say antenna is a band pass filter and transducer. Antennas are essential part in communication systems therefore understanding their basics are important [28].

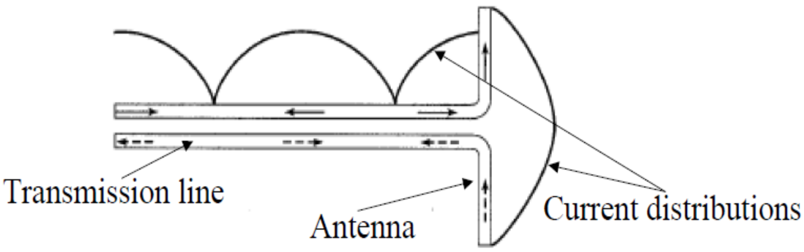


Figure II. 1: Antenna structure

II.2.1 Antenna basic parameters

II.2.1.1 Frequency behavior

a. Input impedance

The antenna is generally considered as a resonant circuit whose resonant frequency is determined from the values of the inductance *L* and the capacitance *C* linked to its structure, its dimensions and the added elements.

We define the quality of adaptation of an antenna either by giving its input impedance Z_{in} (ω) (often 50 or 75 Ω), or by giving its level of reflection coefficient (Γ). The complex input impedance of the antenna is given by the following expression:

$$\boldsymbol{Z_{in}(\omega) = R(\omega) + jX(\omega)} \tag{II.1}$$

With - ***R***: resistance, ***X***: reactance, and **ω** = 2πf.

b. Reflection coefficient

The reflection coefficient is the ratio between the reflected wave at the input of the antenna and the incident wave. It depends on the input impedance Z_{in} (ω) of the antenna and on the characteristic impedance of the transmission line Z_0 such as:

$$\Gamma = \frac{Z_{in}(\omega) - Z_0}{Z_{in}(\omega) + Z_0} \tag{II.2}$$

c. Return Loss (S11)

The return loss (RL) is a parameter that indicates the amount of power that is lost to the load and does not return as a reflection. Waves are reflected leading to the formation of standing waves, when the transmitter and antenna impedance do not match. Hence the RL is a parameter to indicate how well the matching between the transmitter and antenna has taken place. The RL is given by:

$$RL = -20\, log|\Gamma| \tag{II.3}$$

d. Voltage Standing Wave Ratio

As electromagnetic waves travel through the different parts of the antenna system, from the source to the feed line to the antenna and finally to free space, they may encounter differences in impedance at each interface. Depending on the impedance match, some fraction of the wave's energy will reflect back to the source, forming a standing wave pattern in the feed line. The ratio of the maximum power to the minimum power in the wave can be measured and it is called the voltage standing wave ratio (VSWR). A VSWR of 1:1 is ideal. A VSWR of 1.5:1 is considered to be marginally acceptable in low power applications. Minimizing impedance differences at each interface will reduce VSWR and maximize power transfer through each part of the system. The VSWR can be expressed as:

$$\mathrm{VSWR} = \frac{V_{max}}{V_{min}} = \frac{1+|\Gamma|}{1-|\Gamma|} \tag{II.4}$$

e. The Bandwidth

he bandwidth of an antenna corresponds to the frequency band where the transfer of energy from the power supply to the antenna (or from the antenna to the receiver) is maximum. The bandwidth can be defined according to the reflection coefficient (there are no specific criteria for the limit). A typical criterion is to have a reflection coefficient lower than -10 dB (or even aVSWR ≤ 2) on the bandwidth as we can see in (Figure II.2).

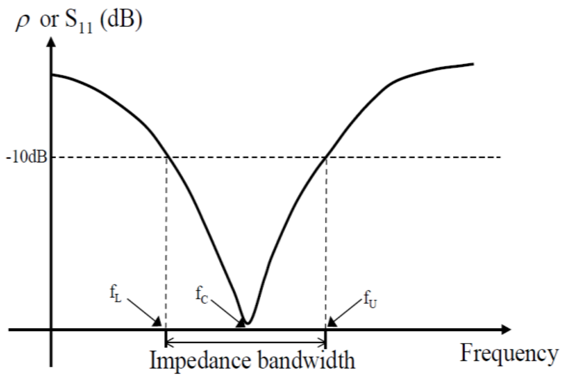


Figure II. 2: Impedance bandwidth.

$$\textbf{Impedance bandwidth} = \frac{f_u - f_l}{f_c} \times 100\%$$

Note that when Γ = -10 dB

$$\text{VSWR} = \frac{1 + |\Gamma|}{1 - |\Gamma|} = \frac{1 + 0.3162}{1 - 0.3162} = 1.93 \simeq 2$$

f. The resonance frequency (f_r)

The antennas are optimized to operate at a particular frequency band and can only be used over this range of frequencies centered on a frequency, called the resonance frequency. In reality, there are several methods (approaches) of analysis which make it possible to determine the link between the characteristics of a patch antenna and its physical parameters. Among these approaches, we can cite the transmission line model (TLM), the cavity and the full-wave model.

Using one of these approaches (TLM), we can determine the resonance frequency of a rectangular patch antenna for the different propagation modes TM_{mn}.

$$f_0 = \frac{c}{2\sqrt{\varepsilon_{reff}}}\left[\left(\frac{m}{L}\right)^2 + \left(\frac{n}{w}\right)^2\right]^{1/2} \quad \text{(II.5)}$$

With *m* and *n* are the mode indices along L and W, respectively.

The effective permittivity is given by

$$\varepsilon_{reff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left[1 + 12\frac{h}{w}\right]^{-1/2} \quad \text{(II.6)}$$

Where ε_r the permittivity of the substrate, *h* is the height of the substrate and *W* is the width of the patch

$$W = \frac{c}{2f_0\sqrt{\frac{(\varepsilon_r + 1)}{2}}} \quad \text{(II.7)}$$

Practically, the length of the patch will take an effective value (L_{eff})

$$L_{eff} = L + 2\Delta L \quad \text{(II.8)}$$

With:

For a given resonant frequency, the effective length of the patch will be expressed by

$$\Delta L = 0.412h\frac{(\varepsilon_{reff} + 0.3)\left(\frac{W}{h} + 0.264\right)}{(\varepsilon_{eff} - 0.258)\left(\frac{W}{h} + 0.8\right)} \quad \text{(II.9)}$$

II.2.1.2 Radiation Characteristics

a. Radiation pattern

An antenna radiation pattern or antenna pattern is defined as "a mathematical function or a graphical representation of the radiation properties of the antenna as a function of space coordinates. In most cases, the radiation patterns determined in the far-field region and are represented as a function of the directional coordinates. Radiation properties include power flux density, radiation intensity, field strength, directivity, phase or polarization." The radiation property of most concern is the two- or three dimensional spatial distribution of radiated energy as a function of the observer's position along a path or surface of constant radius. A convenient set of coordinates is shown in (Figure II.3) and (Figure II.4).

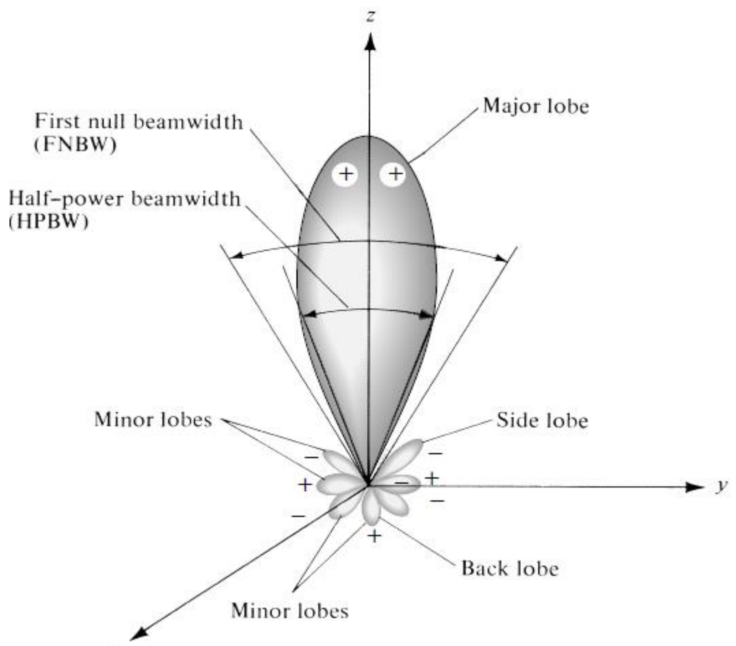


Figure II. 3: (a) Radiation lobes and beam widths of an antenna pattern**.**

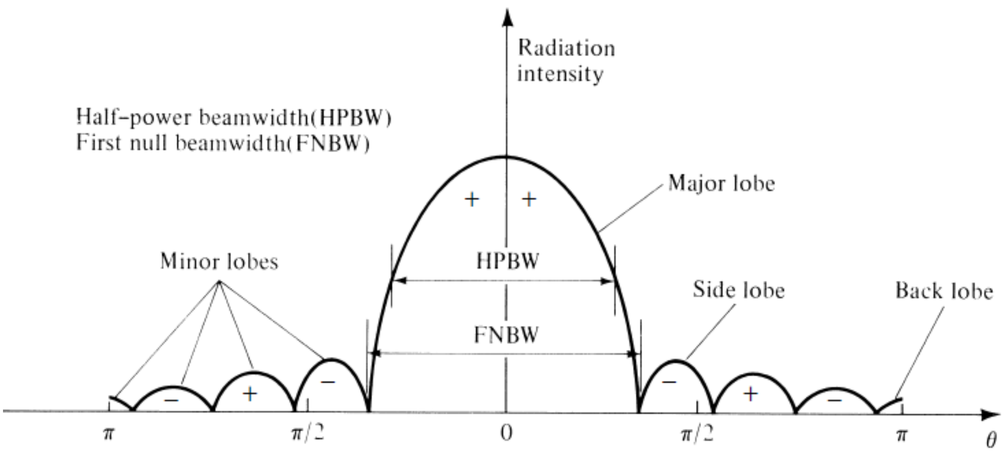


Figure II. 4: Linear plot of power pattern and its associated lobes and beam widths**.**

b. Performance or Effectiveness

The efficiency η of an antenna translates its capacity to transmit electrical power at input Pin into radiated power Pr. It is the ratio between the total power radiated by an antenna and the power supplied to it. The total antenna efficiency e0 is used to take into account losses at the input terminals and within the structure of the antenna. Such losses may be due,to:

1. Reflections because of the mismatch between the transmission line and the antenna.
2. I^2R losses (conduction and dielectric).

The performance of an antenna is defined as follows:

$$\eta = \frac{P_r}{P_{in}} \tag{II.10}$$

c. Directivity

Directivity (sometimes called directional gain) characterizes the way in which the antenna concentrates its radiation in a part of space. It is the ratio of the power radiated in a given direction to the average power that the isotropic antenna would radiate without taking into account the losses. It is defined by the following expression:

$$D(\theta,\varphi) = \frac{P(r,\theta,\varphi)}{P_{iso}} \tag{II.11}$$

P_{iso} is the power density emitted by an isotropic antenna which would have the same emitted power P (r,θ ,φ).

d. Gain

Gain is a parameter that measures the directionality of a given antenna. An antenna with low gain emits radiation about same power in all directions, whereas a high gain antenna preferentially radiates in particular directions. Especially the gain, directive gain or power gain of an antenna is defined as the ratio of intensity of the signal radiated by the antenna in a given direction at an arbitrary distance divided by the intensity radiated at the same distance by a hypothetical isotropic lossless antenna. Since the radiation intensity from a lossless isotropic antenna equals the power into the antenna divided by a solid angle of 4π Steradians,

$$Gain = \frac{4\pi \, radiation \; intensity}{total \; input \; (transmitted) power} \tag{II.12}$$

$$D(\theta,\varphi) = \eta \, D(\theta,\varphi) \tag{II.13}$$

Although the gain of an antenna is directly related to its directivity, antenna gain is a measure that takes into account: the efficiency of the antenna as well as its directional capabilities.

e. Polarization

Polarization of an antenna in a given directions defined as “the polarization of the wave transmitted (radiated) by the antenna. Note: When the directions not stated, the polarizations taken to be the polarization in the direction of maximum gain.” In practice, polarization of the radiated energy varies with the direction from the center of the antenna, so that different parts of the pattern may have different polarizations. Polarization of a radiated wave is defined as “that property of an electromagnetic wave describing the time-varying direction and relative magnitude of the electric-field vector; specifically, the figure traced as a function of time by the extremity of the vector at a fixed location in space, and the sense in which it is traced, as observed along the direction of propagation.” Polarization then is the curve traced by the end point of the arrow (vector) representing the instantaneous electric field. The field must be observed along the direction of propagation. A typical trace as a function of time is shown in (Figure II.5)(Figure II.6).

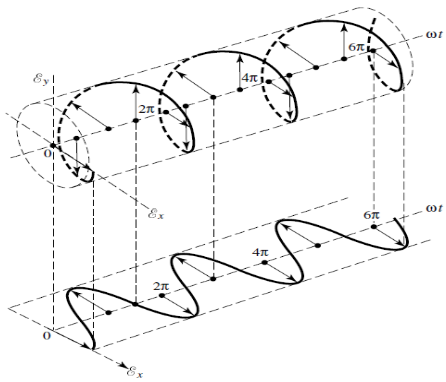


Figure II. 5: Polarization of a Plane Wave - 3D View

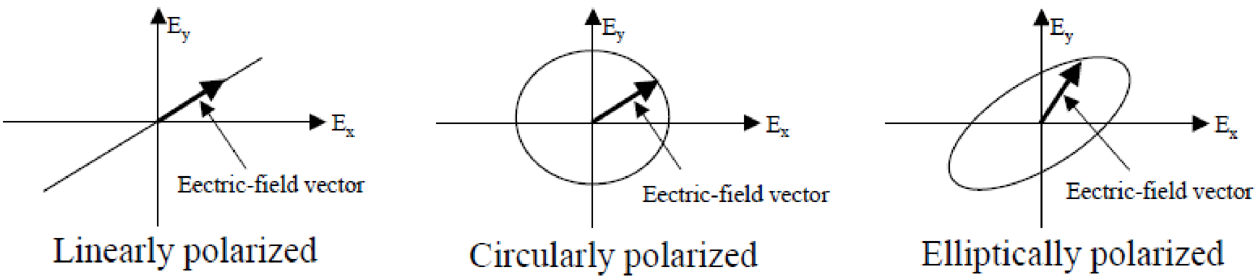


Figure II. 6: Polarization of a Plane Wave - 2D View

In recent years, there has been a wide spread of research and studies on the applications of meta-materials on microstrip antennas. Among the most important applications of meta-materials in the field of micro-strip antennas, we can mention improving the performance of the antenna and reducing its size, in the next papers, we provide a comprehensive and brief overview of the microscope antennas (feeding techniques, pros and cons ....).

II.3 History of microstrip antenna

Deschamps proposed the concept of microstrip patch antennas in 1953 [29]. The first patent of a microstrip antenna design was awarded to Gutton and Baissinot in France in 1955. In the early 1970's the first practical microstrip antennas were fabricated by Munson and Howell [28].The early 1980's was a crucial period in publications, practical realism and manufacturing of the microstrip antennas. Present-day system requirements such as compact, lightweight, low profile conformal antennas that can be directly integrated into a variety of microwave circuits are an important factor in the development of printed antennas. Their low cost and ease of fabrication on printed circuit board (PCB) make them more attractive than the traditionally used lumped element antennas. Microstrip antennas may be made of any geometrical shape and dimension.

II.3.1 Types of microstrip antennas

There are different types of Microstrip antennas which are classified based on their physical parameters. There different types of antennas have many different shapes and dimensions. The basic categories of these Microstrip antennas can be classified in to four [28-30], which are:

- Microstrip patch antennas
- Microstrip dipoles
- Printed slot antennas
- Microstrip travelling wave antennas

II.3.1.1 Microstrip patch antenna

A microstrip patch antenna has a radiating patch on one side of a dielectric substrate having very small thickness and has an infinite ground plane on the other side as shown in (Figure II.7). Dielectric materials may be considered as the backbone of microstrip antennas. The patch is generally made of conducting material such as gold or copper.

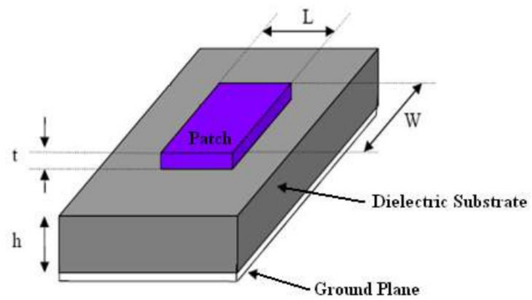


Figure II. 7: Structure of a microstrip patch antenna

To design a rectangular patch, the length L of the patch is usually $0.3333\lambda_0 < L < 0.5\lambda_0$, where λ_0 is the free-space wavelength. Thickness of patch is selected such that $t << \lambda_0$ (where t is the patch thickness). The height h of the dielectric substrate is usually $0.003\lambda_0 \leq h \leq 0.5\ \lambda_0$. The dielectric constant of the substrate (ε_r) is typically in the range $2.2 \leq \varepsilon_r \leq 12$ [28].

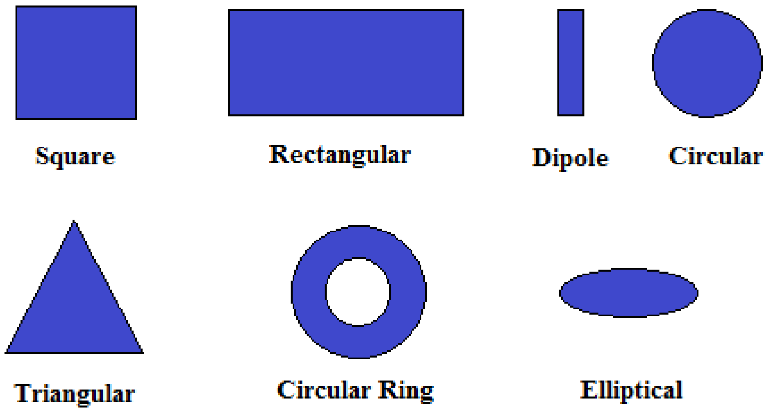


Figure II. 8: Common shapes of the Microstrip patch antennas which are commonly in use.

Substrates with lower dielectric constant are preferred for antenna design for better performance. The possible shapes for conducting patch are shown in (Figure II. 8), but rectangular and circular configurations are most commonly used configurations (Figure II. 9).

The main parameters of a microstrip antenna are its length, width, input impedance, and gain radiation pattern. The length of the antenna should be less than half wavelength in the dielectric.

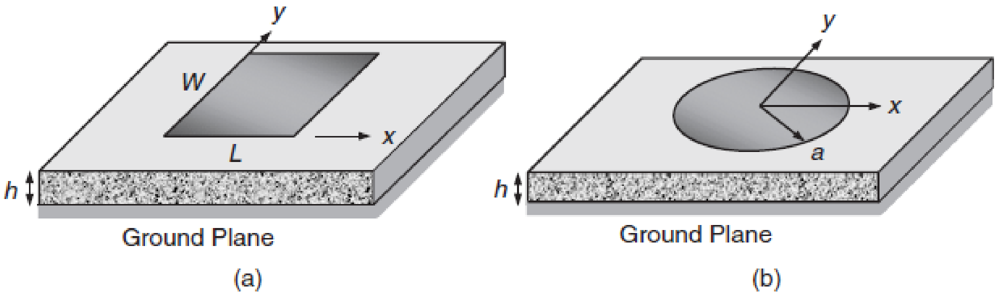


Figure II. 9: (a) Rectangular microstrip patch antenna and (b) circular microstrip patch antenna

II.3.1.2 Feed technique and modeling of microstrip antennas

Microstrip patch antenna has various feeding techniques. As these antennas having dielectric substrate on one side and radiating element on the other, these feed technique can be classified in two different categories: contacting and non-contacting feeds technique.

There are many feed technique, the most popular used are [28]:

a. Microstrip line feed.
b. Coaxial probe feed.
c. Aperture coupling feed.
d. Proximity coupling feed.

Microstrip line and coaxial probe feeds are contacting scheme, in which RF power directly to the radiating patch. Proximity and Aperture coupled feeds are non-contacting schemes, in which electromagnetic field coupling is done to transfer power between the microstrip line and the radiating patch.

There are few factors which lead or involve in the selection of a particular type of feed technique.

The first and the foremost factor is the efficient power transfer between the radiating structure and the feed structure, i.e. the impedance that is matching between the two. The minimization of the radiation and the effect of it's on the radiation pattern is one of the most important aspect for the evaluation of feed.

a. Microstrip line feed technique

Using microstrip line we can give excitation to the antenna as shown in the (Figure II. 10)(Figure II. 11). This method is very simple to design and fabricate. But this technique suffers from some limitations. If substrate thickness is increased in the design then the surface waves and the spurious radiation also increases. Because of that the undesired cross polarization radiation arises.

Microstrip line feeding can be used in the conditions where performance of the antenna is not a strict matter. The edge coupled feed can be improved with coplanar wave guide feeding.

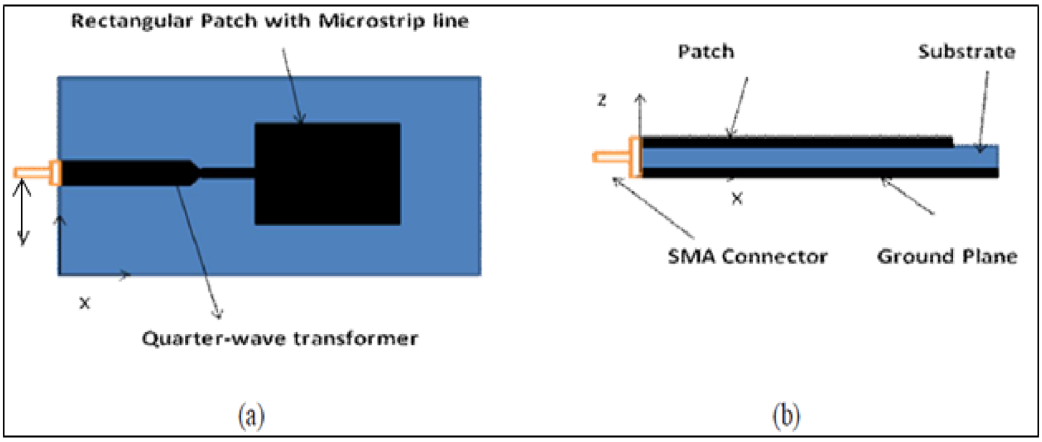


Figure II. 10: Geometry of direct microstrip feed microstrip patch antenna a) Top view b) Side view

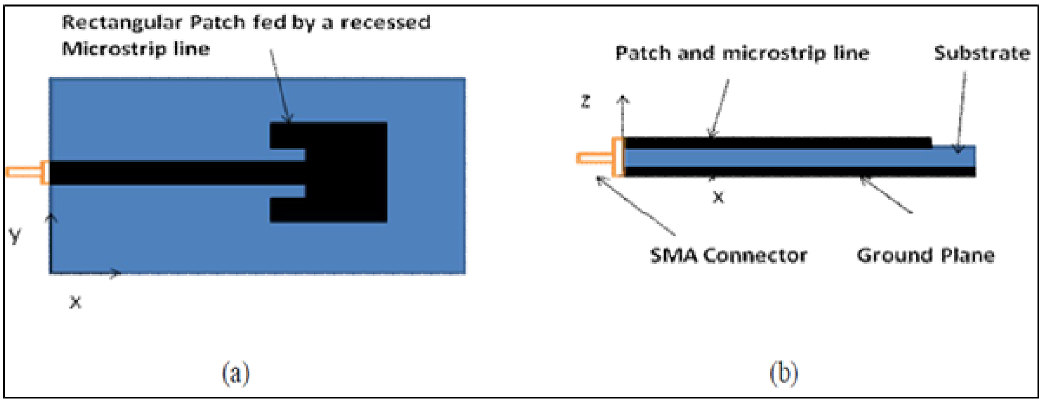


Figure II. 11: Geometry of recessed microstrip line feed patch antenna a) Top view b) Side view

b. Coaxial probe feed technique

The coaxial feed or probe feed is a very common technique used for feeding Microstrip patch antennas. The inner conductor of the coaxial connector extends through the dielectric and is soldered to the radiating patch, while the outer conductor is connected to the ground plane. The main advantage of this type of feeding scheme is that the feed can be placed at any desired location inside the patch in order to match with its input impedance. As shown in the (Figure II. 12) below. To get perfect impedance matching we need to find out the location of the feed point over the antenna element.

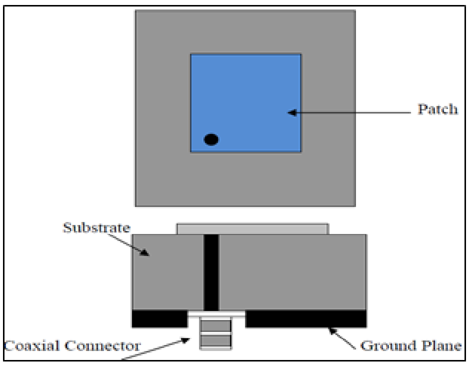


Figure II. 12: Probe fed rectangular microstrip patch antenna

c. aperture coupled feed method

The aperture-coupled configuration consists of two parallel substrate separated by a ground plane. Excitation of the patch is accomplished by coupling energy from a microstrip line through a small aperture in the ground plane as shown in (Figure II. 13). With this arrangement, the microstrip feed is designed on a thin-high dielectric constant substrate, which tightly binds the field lines while the patch is designed on a thick low dielectric constant substrate.

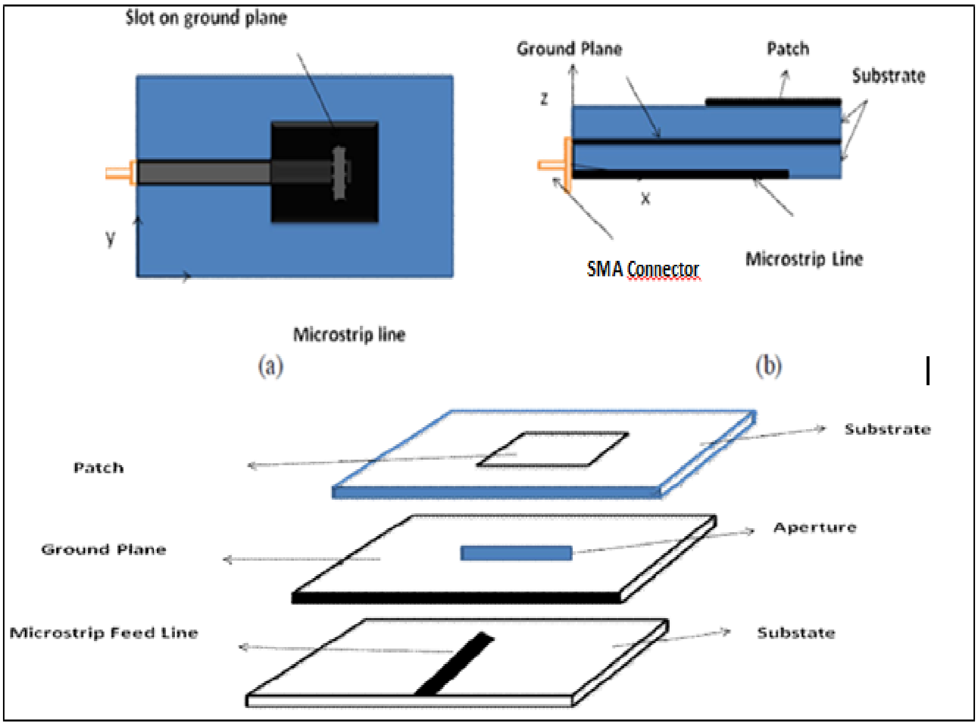


Figure II. 13: Geometry of an aperture coupled feed microstrip patch antenna a) Top view b) Side view c) Pictorial view

d. Proximity coupled method

This is one of the non-contacting non coplanar Microstrip feed technique. Where two or multilayer substrate configuration is considered. Generally in this configuration, microstrip line will be placed on lower substrate and the patch element will be placed on the upper substrate. Other name for this feeding is electromagnetically coupled feed. Capacitive nature will appear between feed lines and patch in this case. By choosing thin lower substrate layer and placing patch on top layer will improve the bandwidth and reduce the spurious radiation. Fabrication of this feeding is slightly difficult because of alignment problems in feed and patch at proper location. Peaceful thing is soldering and related problems can be eliminated.

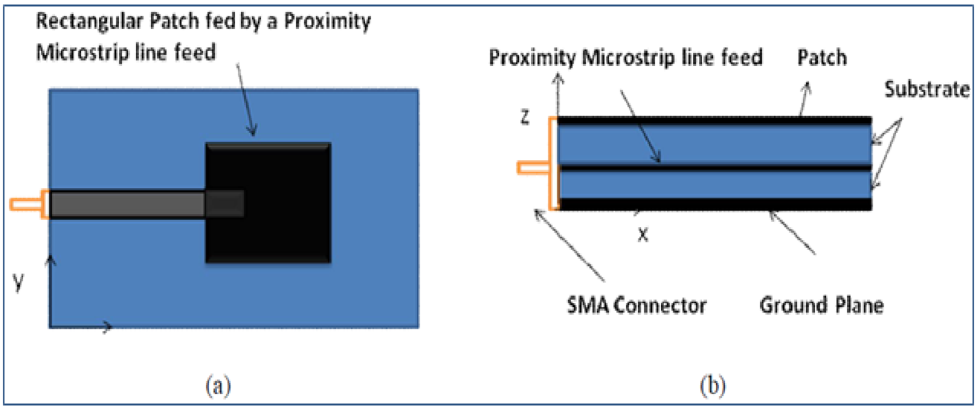


Figure II. 14: Geometry of proximity coupled microstrip feed patch antenna a) Top View b) Side view

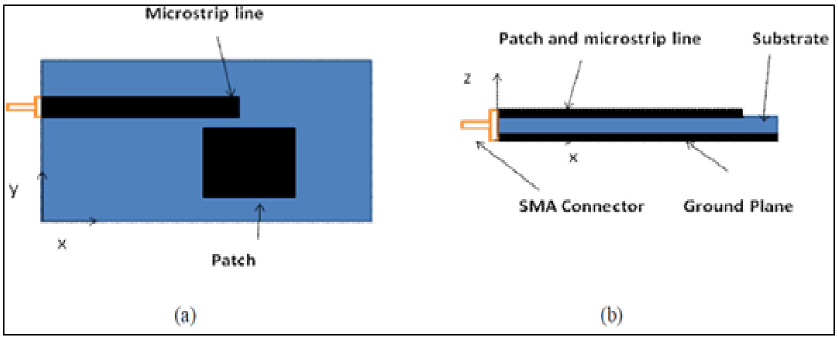


Figure II. 15: Geometry of patch antenna fed by an adjacent microstrip line a) Top view b) Side view

II.3.1.3 Summary of Advantages and Disadvantages of Feeding Methods

Table II. 1: Summarizes the advantages and disadvantages of the four feeding methods discussed above.

	Advantages	Disadvantages
Proximity Coupled	• No direct contact between feed and patch • Can have large effective thickness for patch substrate and much thinner feed substrate	• Easy to match • Low spurious radiation
Microstrip Line	• Monolithic • Easy to fabricate • Easy to match by controlling • Insert position • Easy to match • Low spurious radiation	• Spurious radiation from feed line, especially for thick substrate when line width is significant
Coaxial Feed	• Easy to match • Low spurious radiation	• Large inductance for thick substrate • Soldering required
Aperture Coupled	• Use of two substrates avoids deleterious effect of a high dielectric constant substrate on the bandwidth and efficiency • No direct contract between feed and patch avoiding large probe reactance or width microstrip line • No radiation from the feed and active devices since a ground plane separates them from the radiating patch	• Multilayer fabrication required • Higher back lobe radiation

II.3.1.4 Advantages / Disadvantages and Application of microstrip antennas

The Microstrip patch antennas are well known for their performance and their robust design, fabrication and their extent usage. The advantages of this Microstrip patch antenna are to overcome their de-merits such as easy to design, light weight etc.., the applications are in the various fields such as in the medical applications, satellites and of course even in the military systems just like in the rockets, aircrafts missiles etc.., Some of these applications, advantages and disadvantages are given in the table II.2.

Table II. 2: Summarizes the advantages, disadvantages and typical applications of microstrip antennas

Advantages	• Light weight and low volume. • Low fabrication cost and readily amenable on mass production. • The antennas may be easily mounted on missiles and satellites without major alteration. • Linear and circular polarizations are possible with simple changes in feed position. • The antennas have low scattering cross section. • No cavity backing is required. • Capable of dual and triple frequency operations. • Feed lines and matching networks may be fabricated simultaneously with antenna structure.
Disadvantages	• Due to losses in the dielectric substrate result in low efficiency. • Low gain. • Low power handling capacity. • Poor radiation pattern due to surface waves which travel within the substrate and scatter at surface discontinuities. • Require quality substrate and good temperature tolerance.
Applications	•Satellite communications. •Aircraft antennas. •Missiles and telemetry. •Missiles Guidance Systems. •Environmental instrumentation and remote sensing. •Biomedical Instruments. •Radar systems. •Satellite navigation receiver. •Global positioning system.

II.4 Agile antenna

II.4.1 Definition

A reconfigurable antenna is an antenna capable of modifying its frequency and radiation properties dynamically, in a controlled and reversible manner. In order to provide a dynamic response, reconfigurable antennas integrate an inner mechanism (such as RF switches, varactors, mechanical actuators or tunable materials) that enable the intentional redistribution of the RF currents over the antenna surface and produce reversible modifications of its properties. Reconfigurable antennas differ from smart antennas because the reconfiguration mechanism lies inside the antenna, rather than in an external beamforming network.

The reconfiguration capability of reconfigurable antennas is used to maximize the antenna performance in a changing scenario or to satisfy changing operating requirements.

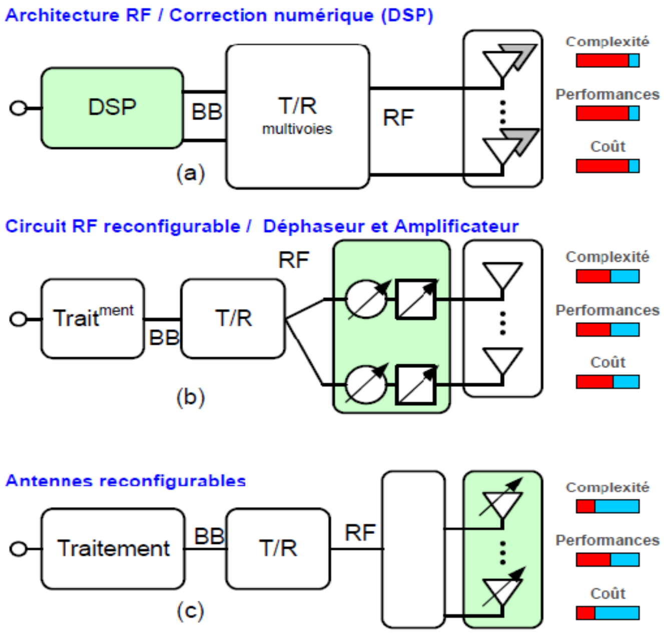


Figure II. 16: Different levels of reconfigurability: (a) Adaptive system by digital processing; (b) Array of phased antennas and (c) reconfigurable antennas.

The basic advantage of such an antenna is that from a conventional fixed operating antenna and by applying a switching technique of an electrical, mechanical, optical or other nature, we manage to extend the capacities and improve the operation and performance of wireless terminals with a minimum impact on the complexity and cost of these systems as shown in the illustrative diagram presented in (Figure II. 16)[31]

II.4.2 Agility Techniques

Advances in microelectronics have offered new ways to obtain reconfigurable antennas through new, more efficient and less costly approaches. Some techniques have used localized active components such as PIN diodes, varicap diodes, MEMS, optical switches ... Integrated into the structure of the antenna, they allow its effective electrical length to be modified , make short circuits or switchable slits, activate or deactivate parasitic elements. Other approaches based on the agility of the substrates are also used. In fact, it has proven to be very useful to use “intelligent” materials, which are to say with characteristic tunable including ferroelectric and ferromagnetic substrates and liquid crystals.

The two main types are the use of electronic components and active materials which change the effective electrical length or the effective permittivity of the structure and thus have different frequency responses.

II.4.2.1 Agility based on integrated components

a. PIN diodes

A PIN diode (Positive Intrinsic Negative diode) is a diode made up of an undoped zone inserted between the two doped zones P and N. Polarized in the direction direct (passing), it offers an extremely low dynamic impedance. Polarized in the opposite direction (blocked) it offers a very high impedance and a very low capacity. For a planar circuit, by placing the diode on the wave propagation path microwave, it is possible to let this signal pass (direct polarization) or reflect (reverse polarization); a switch is produced in this way. This technique is widely used to make agile antennas, whether for frequency agility, for the agility of polarization, or of the phase of electromagnetic waves. In addition, in using PIN diodes with deferential switching voltages, it becomes possible to have more complex agile structures [32]. For circuits intended for applications in free space, it is possible to activate capacitive or inductive elements of the microwave structure (photonic crystal, metamaterial) and thus modify its characteristics. In these devices, the PIN diodes are used in the same way as for a planar circuit: like switches controlled by DC voltage.

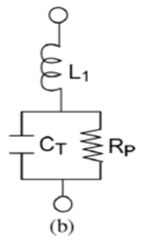


Figure II. 17: Equivalent circuit for PIN diode (a) forward bias (b) reverse bias

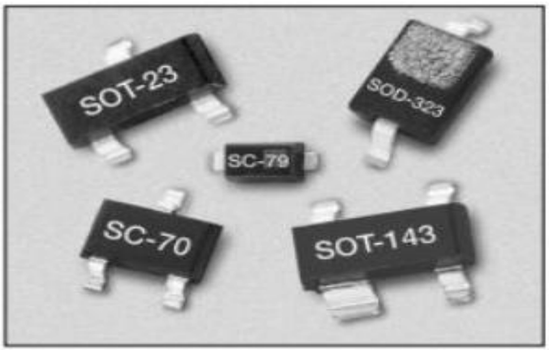


Figure II. 18: Examples of some PIN diodes

Several works presented have used PIN diodes to obtain agile antennas. As an example, a square antenna with a reconfigurable radiation pattern is presented in [33]. The antenna structure includes four short-circuit walls placed respectively at each edge of the square patch, two walls of which are directly linked to the patch and the other two are connected via PIN diodes (Figure II. 19). By monitoring the states of the PIN diodes, the antenna can switch between two different radiation patterns.

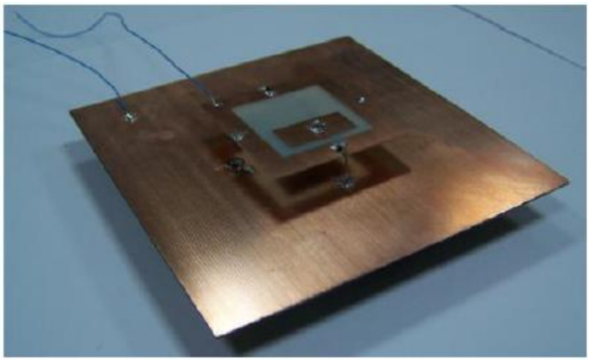


Figure II. 19: Top view of the agile antenna using PIN diodes.

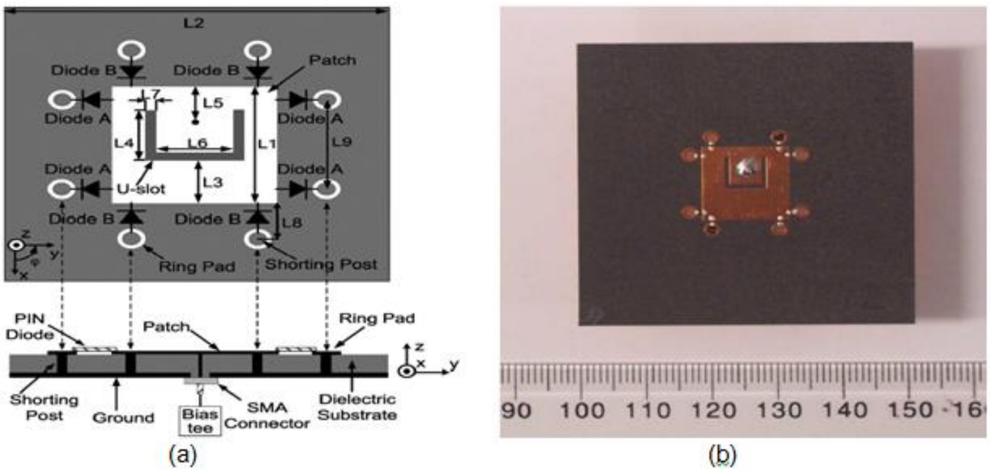


Figure II. 20: (a) Photograph of the pattern reconfigurable U-slot antenna. (b) Schematics of the pattern reconfigurable U-slot antenna

b. Varactor diodes

A varactor diodesor diode with variable capacity is a diode which behaves like a capacitor whose value of the capacity varies with the reverse voltage applied to its terminals (Figure II. 21); when we change its bias voltage, we change the value of this capacity. Although the varactor diodes have a certain ease of integration and great continuous agility, the losses introduced by this component are sometimes significant and the bias voltages can reach 30V. In addition, the complexity of the bias circuit increases with the number of varactor diodes necessary to make the antenna reconfigurable.

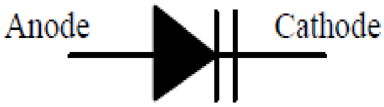


Figure II. 21: Diode varictor.

These diodes are often used to produce agility. For example, in [33], varactor diodes were introduced on two band pass filters (CPW) to obtain the frequency agility of the two wideband CPW antennas as shown in (Figure II. 22). This allows you to control the two rejected bands that are far enough apart from each other so that there is bandwidth between the two. When the eliminated frequency bands are modified using varactors, the bandwidth is also modified.

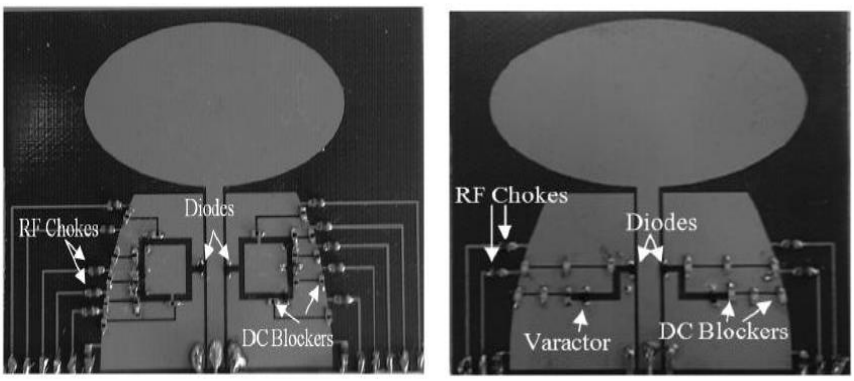


Figure II. 22: The two frequency agile antennas proposed.

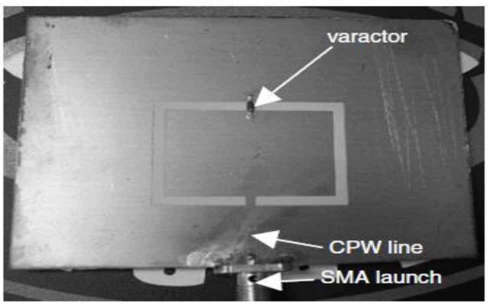


Figure II. 23: Photograph of fabricated coplanar patch antenna with varactordiode mounted at centre of top radiating edge

c. MicroElectroMechanical Systems (MEMS)

MEMS (MicroElectroMechanical Systems) type "RF switches" are components using a mechanical movement which allows obtaining a short circuit or an open circuit on a transmission line. MEMS were developed in the early 1970s and their first commercialization dates back to the 1980s. Since then MEMS have experienced significant development and are still booming [34].

This technology has aroused great interest in the field of telecommunications (satellite reception, wireless telephony.) and in military applications (detecting moving targets, guidance,). Indeed these components present many adventures compared to their direct competitors, semiconductors: reduced losses, more compact components and passive.

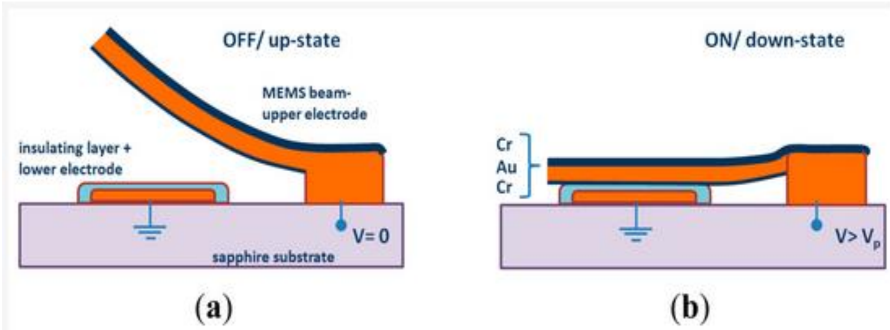


Figure II. 24: Cross sectional view of a cantilever-type beam RF-MEMS showing the two states: (a) non-actuated up-state; (b) actuated down-state when the applied voltage is higher than the MEMS pull-down voltage (V_p).

- ❖ **actuation mechanisms**

From a functional point of view, multi-physical coupling through which mechanical behaviour of movable RF-MEMS parts is controlled (and their characteristics reconfigured) can take place basically according to four different actuation principles: electrostatic, electromagnetic, piezoelectric, and thermoelectric [35]. These different mechanisms are going to be briefly explained.

- ➢ **Electrostatic actuation**. Two electrodes, one fixed and one movable, are necessary, and they must face each other, as in a typical parallel plate capacitance configuration. When a voltage drop is applied across the two faces, the electrostatic attraction force makes the movable electrode approach the fixed one. Above a certain biasing threshold, called ‘pull-in voltage’, the movable part collapses on to the underlying fixed one. (Figure II. 25) shows the schematic cross-section of an electrostatically controlled cantilever MEMS series ohmic switch [6].

In more detail, (Figure II. 25) (a) reports the cantilever switch in its rest position (no bias imposed). In the latter condition, the input/output terminals (T1 and T2) are disconnected, and the micro-relay is in the OFF state, as indicated by the switch symbol above the schematic. However, when a voltage Vbias larger than the pull-in threshold is imposed between the movable (Act1) and fixed (Act2) electrodes, the contact between T1 and T2 is closed, and the switch commutes to the ON state, as indicated in (Figure II. 25)(b).

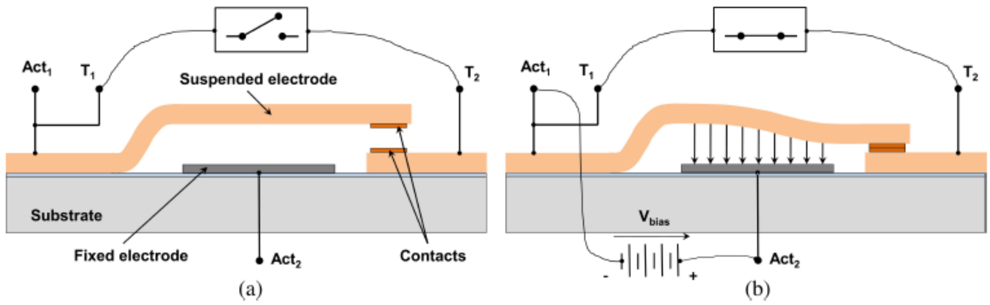


Figure II. 25: a) Schematic cross-section of a cantilevered MEMS series ohmic switch controlled through the electrostatic principle, in the rest position (OFF state). (b) Schematic cross-section of the actuated or pulled-in position (ON state) when a bias voltage is imposed between the fixed and the floating electrode

- **Electromagnetic actuation**. The suspended MEMS membrane has either to be made of or coated with a ferromagnetic material, in order to be sensitive to magnetic field variations. In addition, a magnetic field must be generated by driving a current across a coil, and the former has to surround the deformable membrane.

In such away, when the bias current is imposed, the MEMS part deforms due to the interaction between the magnetic-sensitive material and the external induced magnetic field [37]. The schematic cross-section of a cantilever series ohmic MEMS switch driven through electromagnetic actuation is reported in (Figure II. 26).

In particular, (Figure II. 26) (a) shows the schematic MEMS switch in the rest position, i.e. when no bias current is driven across the terminations Act1 and Act2. In this case, high-impedance is detected between the switch input and output ports, named T1 and T2, and the switch are open (OFF state).On the other hand, when a current is driven through the coil, a magnetic field builds around the MEMS and the latter deforms until reaching pull-in, as shown in (Figure II. 26)(b).In such a circumstance, the impedance between T1 and T2 commutes to a very-low value, due to-the physical contactbetween the two metal patches under the cantilever free end, and the switch is close (ON state).

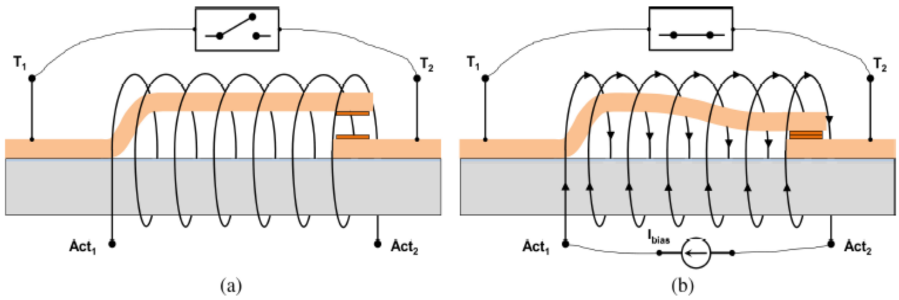


Figure II. 26: (a) Schematic cross-section of a cantilevered MEMS series ohmic switch controlled through the electromagnetic principle, in the rest position (OFF state). (b) Schematic cross-section of the actuated or pulled-in position (ON state) when a bias current is driven through the coil that induces a magnetic field around the movable MEMS membrane (coated with a ferroelectric material).

➢ **Piezoelectric actuation.** The suspended MEMS membrane must be covered/ coated by a thin-film of material holding piezoelectric properties. As known, piezoelectric materials, which fundamentally behave electrically as insulators, exhibit the property of deforming/expanding when subjected to a voltage drop across their opposite faces [38]. As the piezoelectric thin-film is typically patterned above the MEMS structural part (made of gold, silver, copper, etc), its expansion due to the piezoelectric effect results in a downward (momentum induced) displacement [39].

The schematic cross-section of a cantilever series Ohmic MEMS switch driven through piezoelectric actuation is shown in (Figure II. 27). In the MEMS rest position, depicted in (Figure II. 27) (a), the switch is open (OFF state). In contrast, when a bias voltage is imposed between Act1 and Act2, the piezoelectric material expands and induces commutation of the micro-relay to CLOSE condition (ON state) between T1 and T2, as shown schematically in (Figure II. 27)(b).

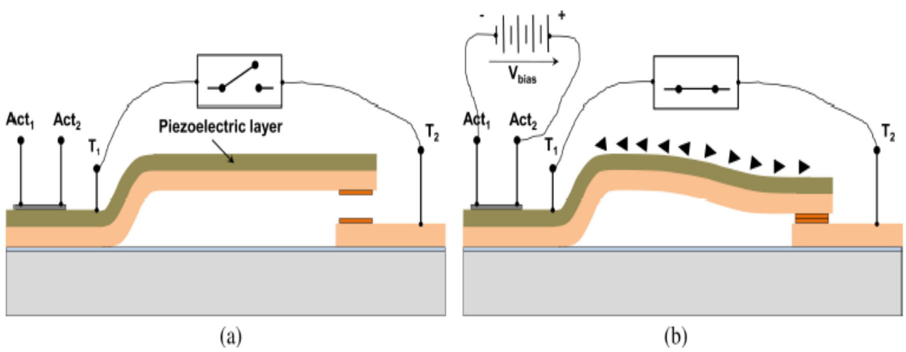
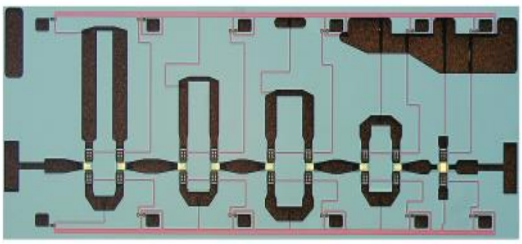


Figure II. 27: (a) Schematic cross-section of a cantilevered MEMS series ohmic switch controlled through the piezoelectric principle, in the rest position (OFF state). (b) Schematic cross-section of the actuated or pulled-in position (ON state) when the piezoelectric film is subjected to a bias voltage

- **Thermoelectric actuation.** In this case, the property of materials thermal expansion is exploited to drive the MEMS movable part/s. An electrical current is driven across the suspended membrane that heats up due to its resistance and, therefore, expands because of the temperature increase [40].

❖ **RF-MEMS reconfigurable phase shifters**

Another class of passive devices that significantly benefits from the exploitation of RF-MEMS technology is that of reconfigurable phase shifters, particularly suited in the driving chain of electronically steerable antennas. An example of an RF-MEMS 5-bit reconfigurable phase shifter in a microstrip configuration is discussed in [41], and its microphotograph is shown in (Figure II. 28) (a). The device features 5 switchable stages (i.e. 5-bit), in which two paths of different lengths can be selected (per each module) by means of RF-MEMS series ohmic switches. The longer denotes the path the RF signal has to travel across, and the larger denotes the phase shift of the output signal with respect to the input, observable through the S21 parameter. The reconfigurable phase shift of each stage (bit) is added to the others, as the 5 blocks are cascaded, thus leading to 32 possible configurations.



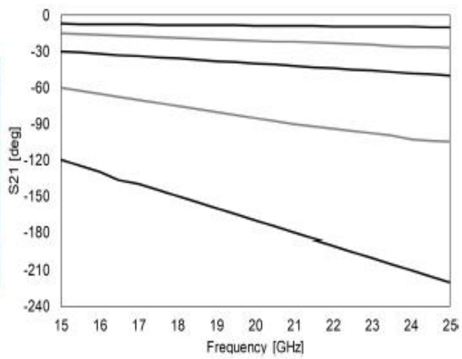


Figure II. 28: (a) Microphotograph of an RF-MEMS 5-bit reconfigurable phase shifter in a microstrip configuration. (b) Input/output phase shift (S21) for different network configurations from 15 GHz to 25 GHz.

The plot reported in (Figure II. 28) (b) shows the measured phase shift (S21) of the RF-MEMS network for a few different configurations, in the frequency range from 15 GHz to 25 GHz. Besides the previously discussed example, the scientific literature reports a wide variety of multi-state RF-MEMS phase shifters.

Another example in [42] where two CPW elliptical monopoles were manufactured on a liquid crystal polymer (LCP) with rejection of reconfigurable band in the frequency band between 5 and 6 GHz (Figure II. 29). MEMS switches are used to activate and deactivate resonant elements without the need to use DC bias lines.

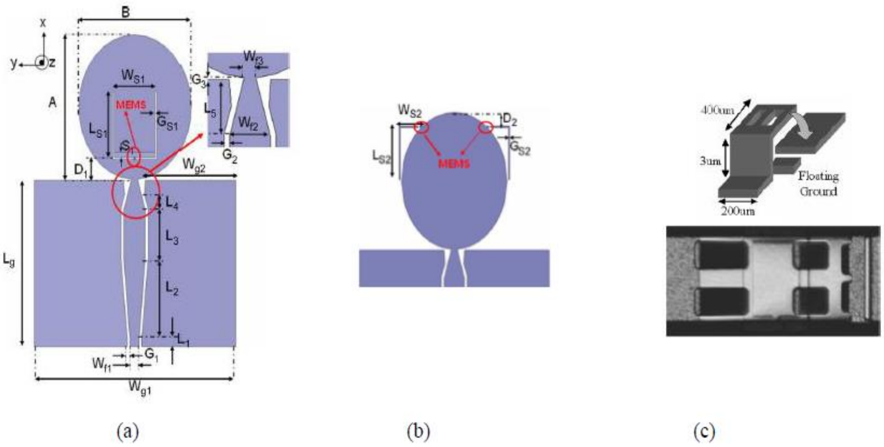


Figure II. 29: (a) Antenna 1; (b) Antenna 2 and (c) MEMS switch used.

The MEMs are distinguished by their very low power consumption and low response time, their simple manufacturing based on micro-machining techniques ... However even today, their long-term reliability remains not guaranteed and their cost of encapsulation still remains high.

d. FET Transistors

Field Effect Transist or (FET) transistors are devices made up of a channel (between source and drain) in which a current modulated by a voltage applied to the grid will flow (Figure II. 30). For microwave applications, the most used FET transistors are the Schottky barrier or MESFET field effect transistors.

When performing agile functions, FET transistors are generally used in the form of MMIC components. An example of agility obtained with FETs can be given through the work of G. Poilasne and L. Desclos which relate to the agility of a network of wires charged by field effect transistors. They extracted two transmission responses possible frequencies of the photonic band gap structure depending on whether the transistor is electronically blocking or passing: the structure behaves as a reflector when the transistors are active (equivalent to a short circuit) and as a simple diffracting structure when the transistors are switched off (equivalent to an open circuit) [3].

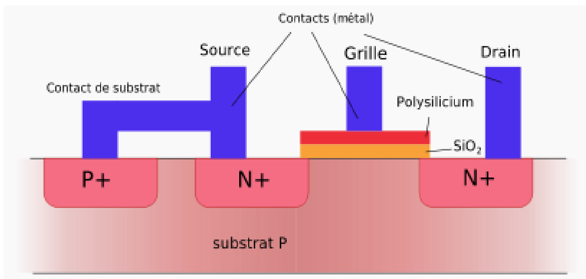


Figure II. 30: Aectional view of a MOSFET transistor

The cut-off frequencies of FET transistors are much higher than those of other active components and can easily reach 100 GHz. These transistors have advantages, in particular in terms of control voltage (3 to 5 V), power consumption (almost zero) or response time (<100 ns). Their high series resistances in the on state (4 to 6 Ω) cause significant insertion losses at high frequencies, which is the main limitation of these devices.

II.4.2.2 Agility based on materials

a. Piezo-electrics

Piezoelectric materials have the property of polarizing dietetically under the action of a mechanical stress (direct effect) and reciprocally deforming them when an electric field is applied to them (indirect effect) Thus, mechanical stress to modify the dielectric constant of the material or conversely an electric field generates a material displacement modifying the conditions of propagation of the electromagnetic wave crossing it. There are many piezoelectric materials Many wall crystals have piezoelectric properties, there are oxides such as ferroelectrics, polymers, ceramics ... The best known is probably quartz, still used in watches to generate pulses of clock. But these are synthetic ceramics, which are the most widely used today in the industry.

Thus, the agility obtained from an electric element is based on a principle of operation similar to micro-electromechanical systems. This constitutes an alternative to MEMS by using devices on a larger geometric scale (a few tens of millimeters). In indirect use, the principle is based on the deformation of a beam of piezoelectric ceramic material under the application of a static electric voltage. The role of the dielectric material is to disturb the propagation of signal in the circuit According to its position above the line of propagation, the equivalent capacity varies in the manner of a diode varactor which modifies the permittivity defective to the constant of propagation and therefore, for example, the phase shift (Figure II.31). Of many guided propagation microwave circuits have been designed using this principle. We can cite the example of a microstrip phase shifter having a maximum phase variation of -450 ′ at 40 GHz for a control voltage of 30 Volts [44].

For free propagation circuits, the use of piezoelectric materials can , like MEMS, move the capacitive or inductive elements of the structure and thus change the characteristics of the wave passing through it.

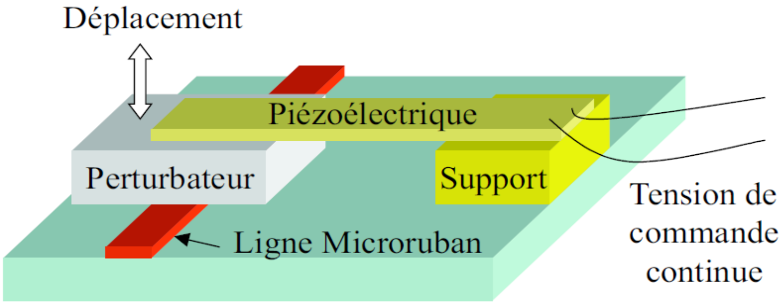


Figure II. 31: Example of the use of the indirect piezoelectric effect in a phase shifter in guided propagation.

b. Liquid Crystals

These materials are called "liquid crystals" because they pass through intermediate phases, or mėsophases, between the liquid state and the solid state. In microwave, we are mainly interested in the nematic intermediate phase. It is an intermediate state between the crystalline solid and liquid phases or the molecules of elongated form are distributed, as in a liquid, without order of position but remaining on average parallel to each other as in a crystal). Their orientation and consequently the components of their permittivity can be modified under the influence of an electric or magnetic field (Figure II. 32)

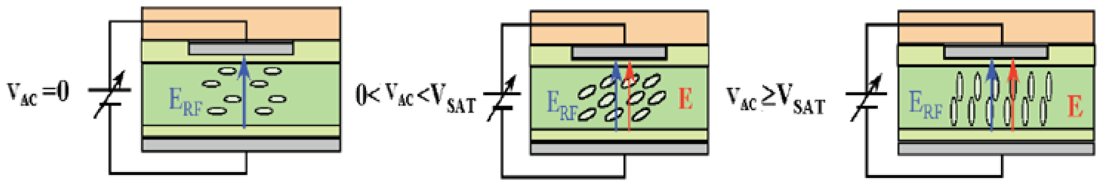


Figure II. 32: Influence of an electric control field on the orientation of liquid crystal molecules.

In the absence of an electric control field, the liquid crystal molecules are aligned parallel to the electrodes by surface treatment (planar orientation). The permittivity seen by the microwave signal is mainly related to the perpendicular permittivity of the liquid crystal, because at these frequencies the material is anisotropic. Under the action of the electric control field, the liquid crystal molecules will gradually orient themselves perpendicularly to the electrodes until saturation (case of positive low frequency anisotropy). The permittivity seen at saturation is then mainly linked to the parallel permittivity of the liquid crystal. The change in permittivity causes a change in the propagation of the electromagnetic wave passing through the material. It is this change in permittivity that is used to make devices.

One of the main advantages of liquid crystals is a weak tilt field, of the order of 1 kV / cm, requiring low control voltages.

The main drawbacks associated with the use of liquid crystals in microwave devices are relatively long response times and the difficulty in using this type of material in circuits.

The first limitation is being overcome, in particular by the association of liquid crystals and ferroelectric materials. The anisotropy must also be improved and the dielectric losses reduced. Finally, the lifetime of such circuits is dependent on the liquid nature of the liquid crystals and therefore on the tightness of the structure. Despite these drawbacks, this route, which is starting to be widely studied for microwave agility, seems promising.

c. Ferroelectric materials

Ferroelectrics are materials with spontaneous macroscopic electrical polarization. They form in subgroup pyroelectric crystals for which the direction of this spontaneous polarization can be oriented or reversed by the application of an external electric field. The name of ferroelectric materials comes from the analogy with ferromagnetic materials. In fact, the macroscopic electrical polarization has a hysteresis appearance as a function of the electric field comparable to the magnetization curve as a function of the magnetic field observable in ferromagnetics. Ferroelectrics are dielectric materials with a dielectric constant very dependent on the applied electric field. The signature of a ferroelectric material is the hysteresis cycle of polarization as a function of the applied electric field (Figure II.33)

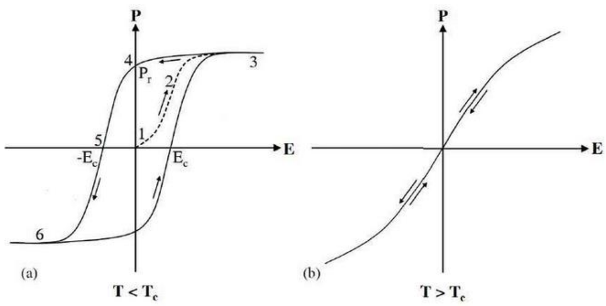


Figure II. 33: Polarization according to the electric field applied for different phases; (a) ferroelectric; (b) paraelectric**.**

It is this property which is used for the production of agile devices. For agile microwave applications, the parlextricphas is used. In fact, in this phase, the dielectric losses are lower than the ferroelectric phase and the voltage control of the permittivity is not of the hyeresis type. On the other hand, in the Para electric phase, the permittivity is less sensitive to the electric control field and can hang strongly from the temperature. A parameter of ferroelectric materials is the Curie temperature (T_c) which corresponds to the transition from ferroglobe phase to tin paraelectric. Above the Curie temperature, we are in the paraelectric phase.

The Curie temperature depends on the chemical composition of the material. For example, the $Ba_xSr_{1-x}TiO_3$, is paraelectric at ambient temperature for a x = 0.6. Whereas for x = 0.8 it is ferroelectric [45] at this same temperature.

Ferroelectrics have dielectric constants strongly dependent on an external electric field and the modification of the permittivity of ferroelectric is at the base of any agile device using these materials. There are many types of ferroelectrics with different chemical compositions; the most used are oxides of perovskite structure such as BaTiO3, PbTiO3 ... Used in the form of ceramic (thick layers) or in thin layers on a substrate of MgO, sapphire or others (Figure II.34). There are many methods for characterizing these materials [46].

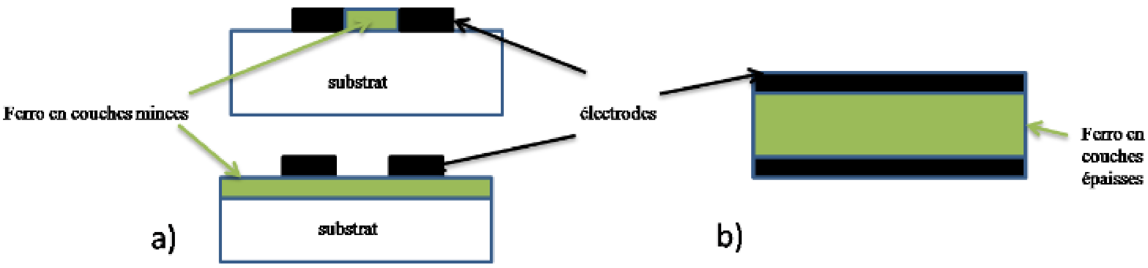


Figure II. 34: Ferroelectric in thin layers located or on the entire substrate b) Ferroelectric ceramic block

Numerous agile devices have been produced in guided propagation: frequency tunable filters, phase shifters, agile oscillators, tunable resonators, and waveguides of adjustable forbidden electromagnetic band [47]. We can also cite the study of an antenna on a BST substrate where the main direction of the radiation is modified by 30 ° for 200V applied [48] Concerning the use of periodic structures in free propagation, Whelan et al have developed an active radome operating between 15 and 18 GHz with ferroelectric FSS [49]. Parker et al also used hole pattern FSSs associated with one or two layers of ferroelectric to shift the bandwidth of their structure from 17 to 2.4 GHz [50]. Finally, let us give the recent example of a one-dimensional photonic crystal serving as a tunable filter at optical and infrared frequencies where ferroelectrics are used as defects in the multilayer [51].

The advantages of using ferroelectric materials are numerous. They have a relatively large dielectric constant allowing miniaturization of the circuits, as well shown in the previous example. The electrical control can easily be integrated into microwave devices and the switching times are low. The main limitation of ferroelectric materials comes from their significant losses in microwave frequencies. They also require a large electric control field (several hundred KV / cm) but the problem can be overcome by reducing the thickness of the substrate of the material.

d. Magnetic materials

Ferrites are dielectric and ferromagnetic materials whose permeability is controlled by applying an external magnetic field .The condition necessary for the use of ferromagnetic materials in microwave is to use them at a frequency higher than the frequent fm (called gyromagnetic resonance frequency) to overcome the significant losses linked to the gyromagnetic resonance of magnetic moments and to relaxation.

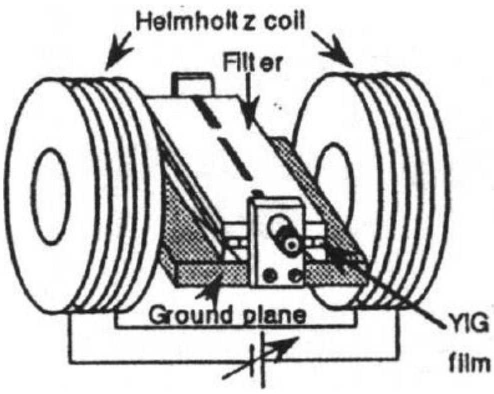


Figure II. 35: Filter with ferrite substrate controllable with Helmholtz coils**.**

Most agile devices developed from ferrites use tunable substrates. We can mainly find phase shifters and tunable filters. Let us quote the case of a radom for a printed antenna with frequency of controllable radiation [52] Concerning the periodic structures, Parker et al have measured the transmission of an FSS with metallic square patterns of periodicity 11mm, length 6mm and width 0.8 mm, printed on a ferrite substrate [53]. Without a magnetic field, the resonance frequency is 9GHz, by applying 4000 G, it shifts to 14GHz, i.e. 55% agility.

It is therefore quite possible to achieve significant agility of the circuit by magnetic materials. However, this principle comes up against the difficulty of generating a magnetic field. Magnetically controlled circuits require the use of a large magnetic field, obtained by means of electromagnets which are bulky and consume electrical power.

This limits the miniaturization of this type of circuit because by decreasing the size of the coils, the applied magnetic field decreases. Furthermore, it should be noted that the response time of circuits with a magnetic substrate is directly linked to the time constant of the coil of the magnetic control field. Another limitation to this type of agile circuits is the high conductivity of these materials, leading to large leakage currents.

II.4.3 Comparisons of methods to achieve agility

After the different techniques for making agile microwave, devices have been detailed in two parts: one for the use of components, one for the use of materials. We will now compare the available solutions by highlighting the advantages and disadvantages of each method to obtain the agility of the system.

The different means are compared on a few main criteria: the agility of the structure, the quality factor, the power consumption, the control voltage, and the response time of the system and an evaluation of the cost of production.

We also add the degree of ease of integrating the component or material into the structure, as well as the integration of the command necessary to get agility. In Table II. 3 the strong points of the methods and the weak points, the X crosses means that no data was noted.

Table II. 3 : Comparative of most solution realize agile antenna

Solutions	Diodes FET	MEMS	Ferroelectric	Ferromagnetic	Liquid Crystals
Agility	High	Medium	Medium to high	High	Medium
Quality factor	Medium (30-60)	High (>100)	Medium (30-100)	**X**	**X**
power consumption	High (1-5 mW)	Low (1-5 µW)	Low (1-5 µW)	**X**	Medium (<100 µW)
Control voltage	Low (1-30V)	Medium (10-100V)	Medium (10-100V)	**X**	Low (<30V)
Response time	Good (qqes ns)	Medium (>5µs)	Good (<1ns)	Good (<1ns)	Low (>10ms)
Integrations	Limited	Easy	Easy	Difficult	Medium
Cost	Medium	Medium	Low	Medium	Low

II.4.4 Classification of reconfiguration

Whatever the reconfiguration technique used, they can be classified according to their functionality on the characteristics of the antenna (frequency, spatial (radiation) or on polarization).

a. Frequency reconfiguration

Frequency reconfigurable antennas have attracted a lot of attention because of their ability to span multiple frequency bands to significantly reduce the number of antennas required for multi-mode communication.

These antennas are also called tunable antennas and are classified into two continuous and discrete categories. Continuous tunable antennas allow passage between bands and offer the possibility of varying one or more resonant frequencies continuously.However, the second category allows the antenna to switch between several frequency bands.

To better understand frequency reconfiguration, we take the example of the WIFI application (2.4 GHz: 802.11b standard). This service includes several ISM frequency channels. A frequency reconfigurable antenna for the WIFI application must be designed to cover all the previous channels by switching. The instantaneous bandwidth must be large enough to cover each channel and the frequency agility makes it possible to move from one channel to another [54].

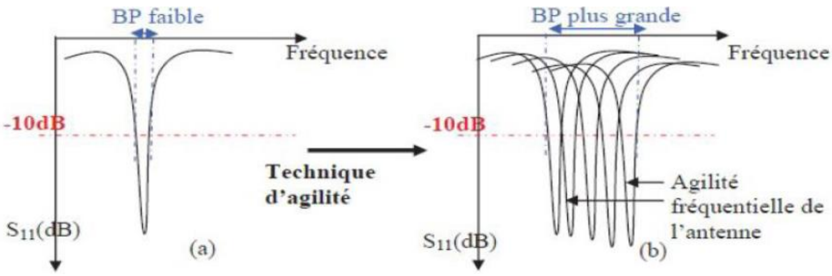


Figure II. 36: Illustration of frequency agility

- **Principal of frequency reconfiguration**

Frequency reconfigurable antennas allow the operating frequency to be adjusted dynamically. They are particularly useful in cases where several communication systems converge, because the multiple antennas required can be replaced by a single reconfigurable antenna. Frequency agility is achieved by changing the resonance length of the resonator.

To do this, the antenna is loaded by active elements whose reactance can be controlled electronically (varicap diode), or by components acting as a switch (PIN, FET or MEMS diode). These active components require biasing circuits to make the switching (ON-OFF).

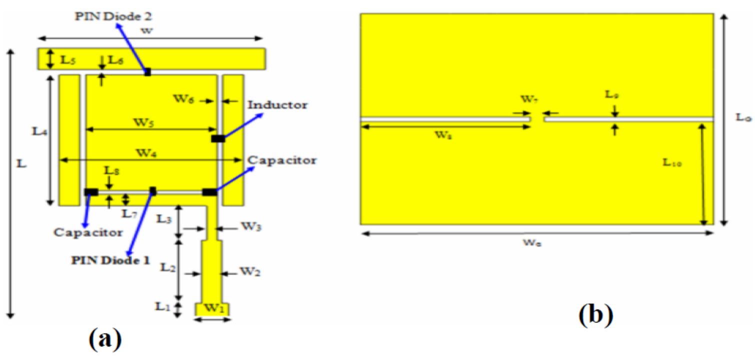


Figure II. 37: Frequency configurability using a rectangular antenna seen from above (a) and below (b)

b. The reconfiguration of radiation

The reconfiguration of the radiation allows the antenna to adapt its radiation pattern and maintain its operating frequency. This type of reconfiguration is used to orient the main lobe towards the useful directions and cancel the radiation. In the directions of interference, this improves the capacity of the system. The reconfiguration of the radiation allows the antenna to modify its shape, its direction and its gain in order to favor the preferred directions. Antenna arrays are often used to fulfill this task [55].

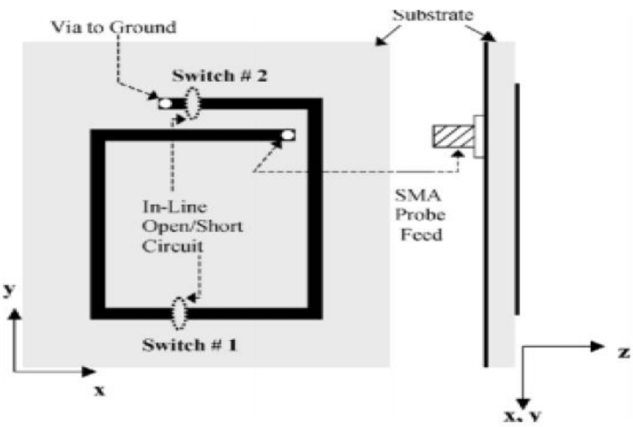


Figure II. 38: Configurability of radiation using a wired square spiral antenna

❖ **Principal reconfiguration**

The geometry must present several reconfigurable current paths, but these must be similar, which aims to maintain the operating frequency while modifying the shape of the radiation diagram.

❖ **Reconfiguration mechanisms**

Mainly, the radiation diagram setting is based on the mutual coupling between the main element and it's parasitic. Therefore, the changes in the radiation patterns are obtained through changes in the coupling between the elements, which, in turn, change the supply currents on both the main element and the parasitic elements [56].

c. Reconfiguration in polarization

The polarization reconfiguration allows you to change the polarization of an antenna (horizontal / vertical, left or right of circular polarization, etc.). This type of configuration increases the reliability and robustness of the communication (immunity to interference) as well as providing an additional degree of freedom (diversity). In order to maintain the other characteristics (frequency, radiation diagram), the polarization of the antenna must be altered by acting on the phase and direction of the supply current.

We can change the polarization of the antenna by modifying the vectorial orientation of the E field and this without altering neither the resonant frequencies, nor the shape of the radiation diagram [57].

❖ **Polarization reconfiguration mechanisms**

The mechanisms for achieving this reconfiguration are, in large part, the same as those described for frequency and radiation reconfiguration, but their implementations are necessarily different.

An example of a reconfigurable antenna is the patch antenna with switchable slots, or "PASS" developed by UCLA [II.29]. By inserting a switch (PIN or FET diode) in the center of the slot (Figure II. 39)(b), controlling the current behavior on the patch by using a biasing circuit which allows switching the diodePIN from On state to OFF state and vice versa. A different polarization can be achieved by using two orthogonal slits on the patch [58].

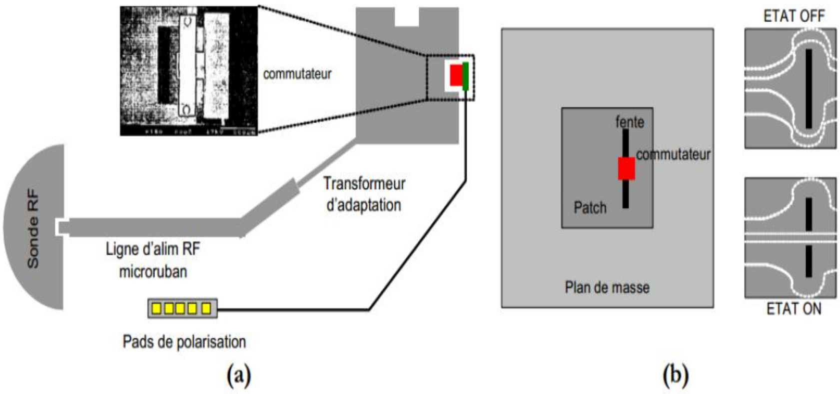


Figure II. 39: Patch on-board switched antenna in (a) and UCLA PASS antenna in (b)

II.5 Interest and applications of reconfigurable antennas

The main interest of reconfigurable antennas resides in their capacities to bring additional functionalities and degrees of freedom to the communication and telephony systems, so as to improve their performance.

For example, in the case of a link between a portable device and a base station, the antenna of the portable device is strongly constrained in its design by the energy and the space available, as well as by the cost restrictions, and it is not common for several antennas to be used to increase diversity [59]. Typically, the device is in unpredictable or difficult conditions and the connection is not optimal. In this context, reconfigurable antennas can be particularly useful: a tunable antenna will allow you to change the operating band, to filter the interference or even to tune the antenna resonance frequency to take into account a new environment.

A reconfiguration of the radiation pattern can direct the beam to the base station, resulting in reduced transmit power and therefore energy savings for the battery.

Another example are the traditional phased networks, which have well-known limitations in terms of bandwidth and scanning angle: to exceed the usual structure based on a periodic distribution of identical elements by adding reconfiguration can improve the instantaneous bandwidth, the angular scanning range or the lobe distribution.

For applications using UWB (Ultra Wide Band) which suffer from coexistence with narrow bands (for example the WLAN 802.11a band at 5-6 GHz for UWB 3-10 GHz)[60 - 61], antennas capable of Rejecting these narrow bands or switching between wide band and narrow band are particularly useful [62].

Multi-antenna techniques such as MIMO (Multi Input Multi Output)[II.34],also benefit from the diversity provided by reconfigurable antennas, since one condition is necessary for the proper functioning of the system is that multiple antennas generate almost uncorrelated signals [63].In this context, a diversity of polarization and radiation patterns, and even of frequency in MIMO-OFDM (Orthogonal Frequency Division Multiplexing) systems is particularly important.

Reconfigurable antennas also find their interest in complex and demanding systems in reconfiguration such as software radio (or SDR: Software Defined Radio) which allows to mix hardware and software adaptations with great flexibility. Even more advanced, cognitive radio makes it possible to add artificial intelligence and awareness of its environment to SDRs [64].

Cognitive radio can possibly dialogue with another cognitive radio, optimizing the links by limiting interference with close users, or taking into account the spectral congestion at a given time, by "scanning” a broad band [65].

The abovementioned techniques and systems find their interest for civil but also military applications, where anti-jamming, the security of communications and the dynamic reconfiguration of the links to prepare for all Contingencies are crucial features. Generally, at the same level of functionality, a reconfigurable antenna has many advantages over a system composed of several single-function elements: potentially it will allow a gain in volume, weight, maintenance costs, even durability by adapting to new standards.

II.6 Advantages and disadvantages of a reconfigurable antenna

- **Advantages**

The advantages of reconfigurable antennas are:

- Reallocation and dynamic management of the spectrum.
- Offers flexibility and meets wireless radio platform requirements (multiple services in one antenna).
- Reduction of the number of antennas in the system which reduces the size and cost of the antenna.
- Good insulation between the different wireless standards and the bands.
- The reconfiguration of radiation allows for spatial diversity.
- Frequency reconfiguration is useful in support of many wireless applications.
- Reconfiguration in polarization makes it possible to reduce various problems such as the weakening of the signal due to propagation by multipath, the sensitivity of the transceiver to the orientation of the antenna and the security, etc.

- **Disadvantages**

Despite the advantages that we mentioned above, the reconfigurable antennas also have disadvantages which are [66]:

- More expensive than conventional antennas (introduce active components).
- High energy consumption (active components to be polarized continuously).
- Design and simulation difficulties due to the integration of the active components in the antenna (the need to use packages, polarization circuit).
- Reduced efficiency.

II.7 Conclusion

In this chapter, we covered the basic initiatives of microstrip antennas and reconfigurable antennas and their necessity in the telecom field. This was done by revealing the basic parameters and properties that affect the behavior of the antenna. And we also compared the available solutions by highlighting the advantages and disadvantages of each method to obtain the agility of the system. Different methods were compared based on a few key criteria: body agility, quality factor, energy consumption, control voltage, system response time and production cost assessment.

What we can recapture from this chapter is that the important parameters is that The challenge of reconfigurable antennas consists not only in obtaining the necessary level of functionality, but also in integrating these functionalities in complete effective systems, reasonably complex and in expensive .

Consequently, several data must be analyzed precisely to evaluate a technology of reconfigurable antennas. First, reconfigurable antennas are expected to exhibit the performance level required for a given application in all of their configurations. The operating parameters described in section II.2.1, in particular the adaptation, the bandwidth, the gain, the radiative efficiency or the shape of the radiation diagram must be satisfactory over the entire range of reconfiguration and if possible decoupled.

Chapter III

Frequency agile antennas based on metamaterials

III.1 Introduction

Still with the aim of agility systems, researchers and manufacturers are developing components with multiple, even intelligent, functions. The multi functionality and flexibility of the devices are obtained thanks to architectures and by the use of electronic controls, today we find a new term called “Metamaterials”, they have many areas of use, like Suppleness, clocking and antenna.

Metamaterials are artificial structures designed to have proprieties not available in nature. They resemble natural crystals and are built from periodically arranged square unit cells. Each unit cell has side length of ‘a’. This unit cell interacts with an external electromagnetic wave that has a wavelength λ, to verify the homogenization criterion the largest unit cell dimension must be a small fraction of the wavelength. The manner in which the incident light wave interacts with these meta-atoms of the “metamaterials” determines the medium’s electromagnetic properties.

In the field of telecommunication, antennas are essential components for their multiple uses, and now it is entering the five generation with high Frequency.

In standard case, each antenna has one operating frequency. In this work, thanks to metamaterials, we project design one antenna with several operating frequencies. This is known as “Agility on frequency”.

III.2 Objective

The main objective of this chapter to realize a metamaterial based agile antenna, this is achieved by using an agile metamaterial unit cell which can exhibit different behaviors, thanks to an external switching control system. The control system consists in different switches placed on the unit cell. According to the switches states (ON or OFF) one can program the unit cell to a desired behavior, this lead to a metamaterial which electromagnetic response can be tailored in demand. Our agile metamaterial, according to the switches state, can behave either as a dielectric medium or as a conducting medium. By replacing the conducting surface of a microstrip antenna, by the agile metamaterial, we can control the area of the antenna radiating element which determines the operating frequency.

III.3 Agile and programmable Metamaterial characterization

III.3.1 Characteristic of the unit cell

Metamaterial structures based on crosse type conductors are mostly used in metamaterial unit cell design due to the fabrication ease. It is formed by two dipoles at 90° to each other, as shown in the (Figure III. 1). This structure represents the elementary unit cell in the construction of our metamaterial, which will be used later to control the resonant frequency of microstrip patch antenna. The patterns used here are made from copper conductive tape whose conductivity is of the order of 58.000.000 S/m, printed on a dielectric substrate (Rogres RT/Duroid 5880) characterized by a relative permittivity $\varepsilon_r = 2.2$ and a relative permeability$\mu_r = 1$, and with dielectric loss tangent around 0.0027.

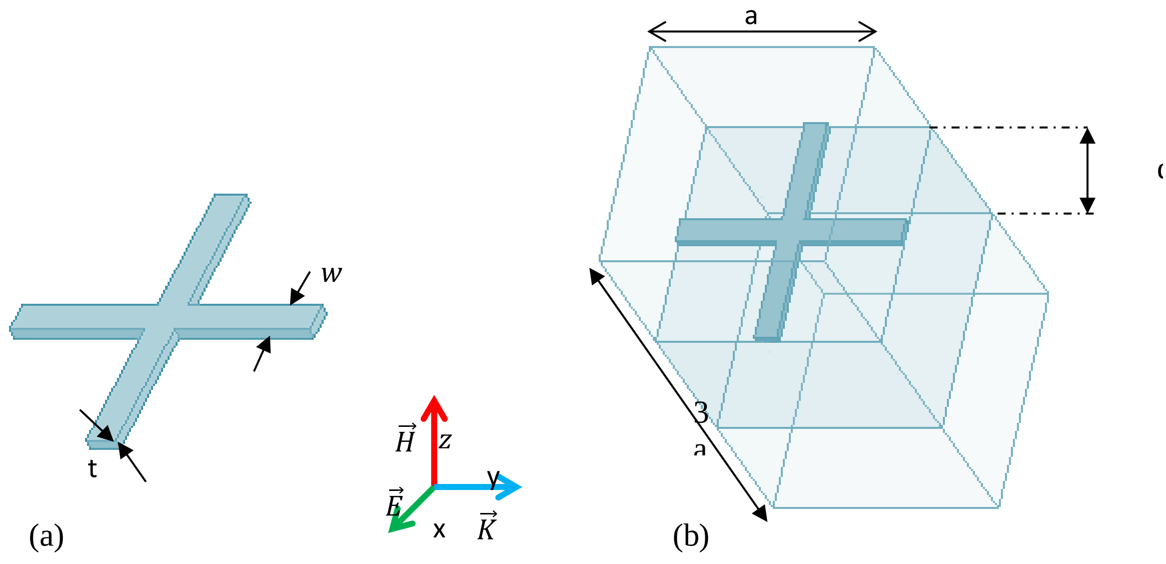


Figure III. 1: Metamaterial unit cell geometry

In this works, the antenna operating frequency is 22GHz, so the corresponding wavelength in free space is $\lambda = 13.6mm$. to reach the homogenization criterion, the largest unit cell dimension is set to a smaller than wavelength (λ/7).

III.3.2 Agile metamaterial cross type unit cell

Our agile unit cell is composed of a disconnected cross type conductor of width *w* and metallic thickness *t* printed on a dielectric slab of thickness *d* as depicted in)Figure III. 2.(

The ends of the disconnected cross branches are all terminated by switches as shown in (Figure III. 3). Generally, we use as switching devices PIN diodes, MEMs, etc. Each unit cell can be connected to its four neighbors by the four switches to constitute the agile meta-surface According to the switches states (ON or OFF), the agile unit cell can flip between two different commutable behaviors. The first one, when the four switches are in the ON stats, corresponding to a conducting medium and is named as connected cross type metamaterial. The second one, when the four switches are in the OFF stats, corresponding to a dielectric medium and is named as disconnected cross type metamaterial. Every region of the agile metamaterial can be programmed (acting on the switches states) to behave as a disconnected cross type (switch OFF) or as a connected cross type (switch ON) metamaterial.

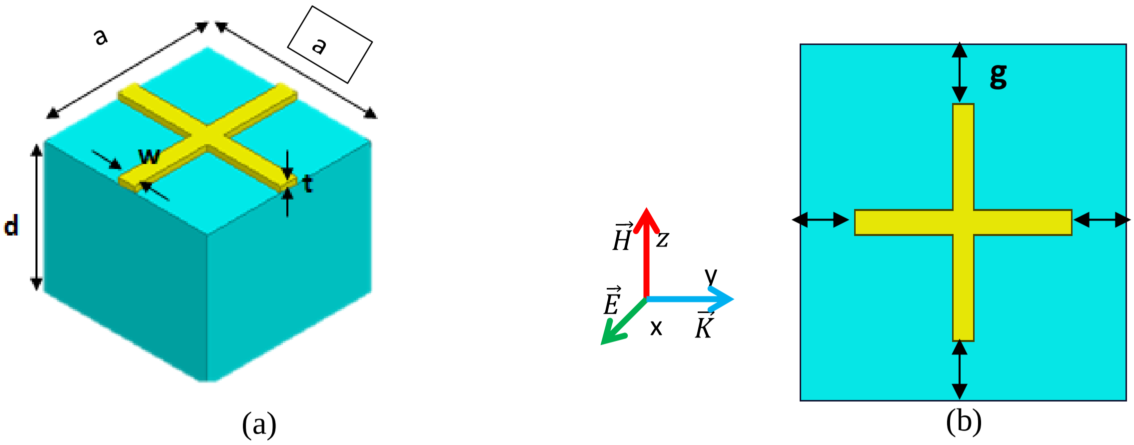


Figure III. 2: Agile metamaterial elementary cell (a) connected cross (b) disconnected cross.

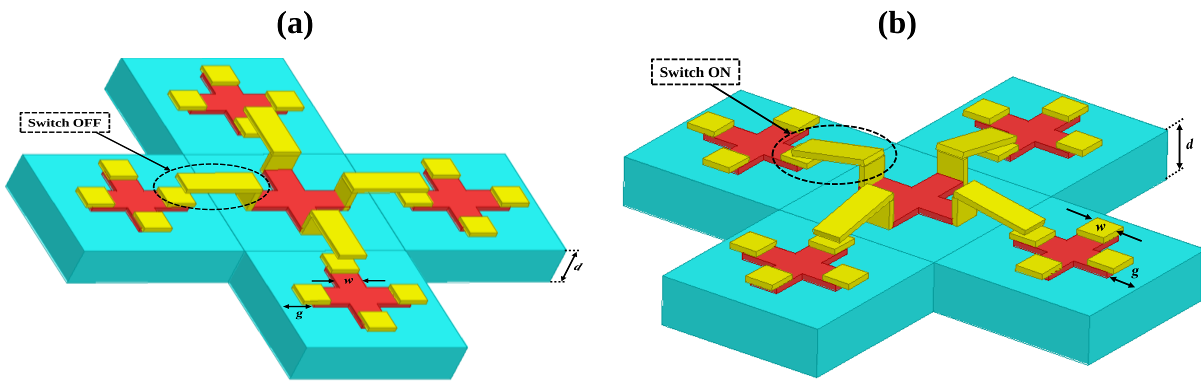


Figure III. 3: (a) Agile unit cell switch OFF, (b) Agile unit cell switch ON.

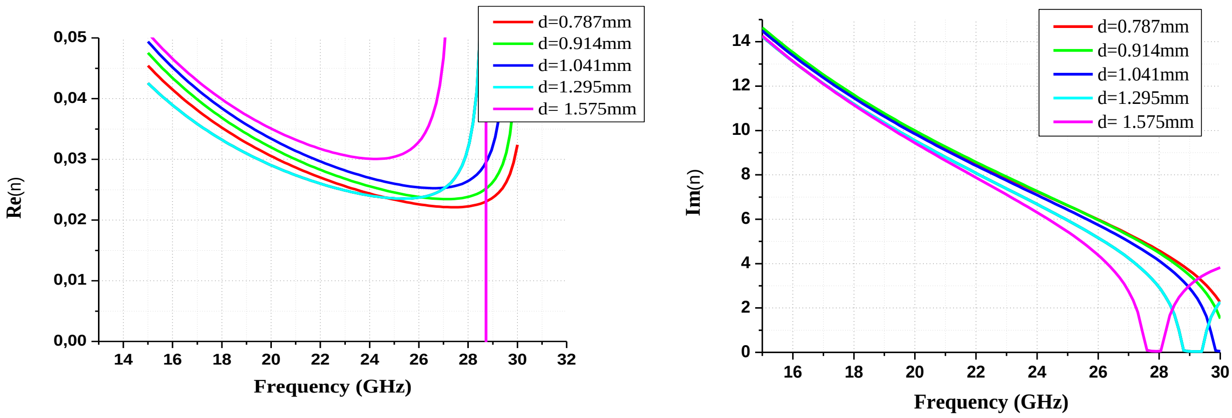
III.3.3 Effect of unit cell geometrical parameters (d, t, and w) on the metamaterial electromagnetic behavior (εeff μeff, and n)

The metamaterials are formed and tailored to respond to desired electromagnetic properties, to behave as a homogeneous material accurately described by an effective constitutive parameters. The unit cell dimension must be much smaller than the wavelength.

The operating frequency is 22 GHz, and consequently, the corresponding wavelength in free space is λ=13.6 mm. Hence, the period "a" of the metamaterial unit cell must be much lower than λ/7≈ 1.94 mm, we have fixed the period at a = 0.5 mm. The others unit cell parameters such as (t, d, and w) can be optimized to obtain the desired metamaterial behavior (unit cell tailoring).

III.3.3.1 Effect of the substrate thickness "d''

In order to investigate the influence of the dielectric substrate thickness d, we fix the conductor metallization thickness to t=0.035 mm, and the conductor width to w=0.15 mm, and we choose for "d" different standard values available in datasheets.



(a) (b)

Figure III. 4: Refractive index n for different values of d: (a) Real part, (b) imaginary part.

According to the figure, we notice each time that the substrate thickness is increased, the curves approach to zero.

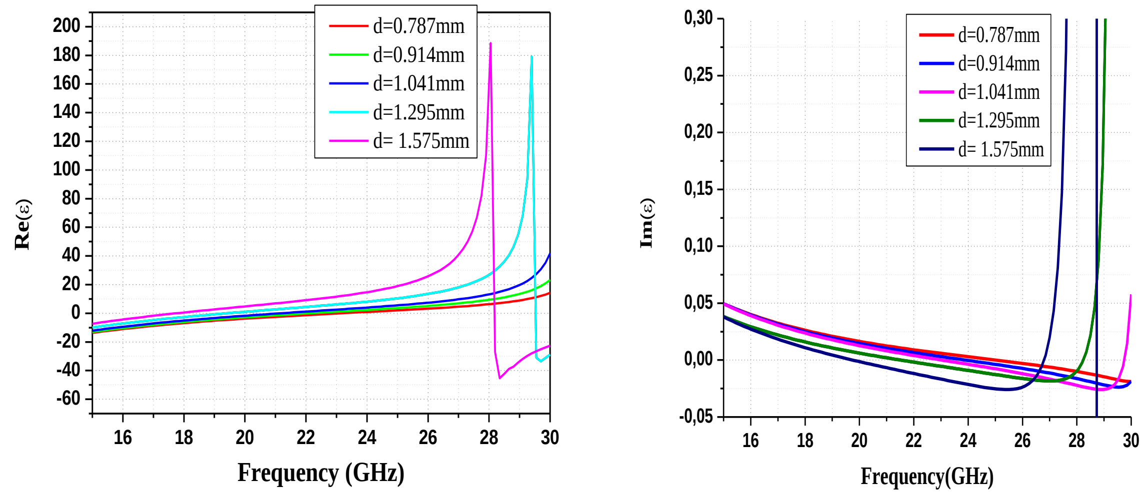
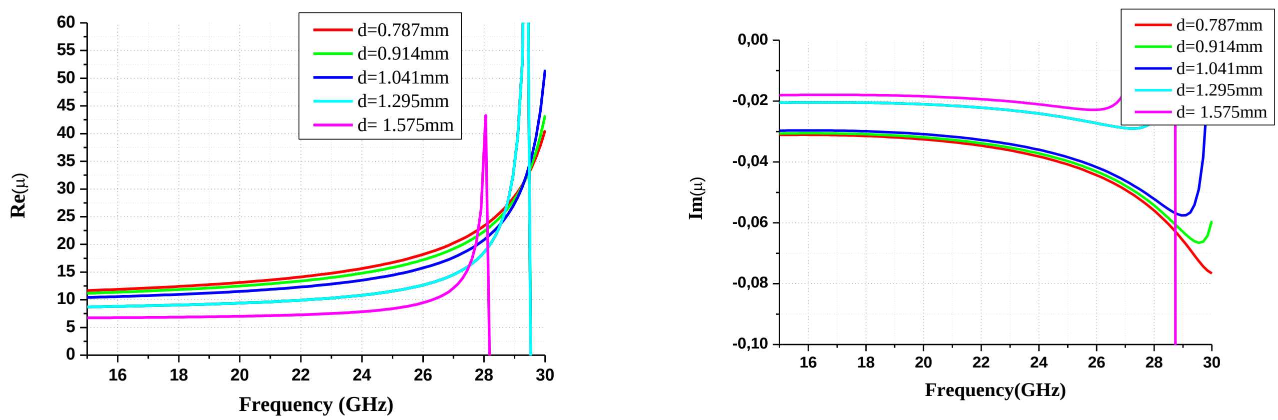


Figure III. 5: Effective permittivity for different values of d: (a) Real part, (b) imaginary part.

In (Figure III. 5) we study the permittivity real and imaginary part, the real part we seen the intersection field between 20-23GHz. when the thickness equal d=0.914mm the Frequency plasma equal exactly 22GHz. So we take this thickness for cell type cross and for antenna patch.



(b)

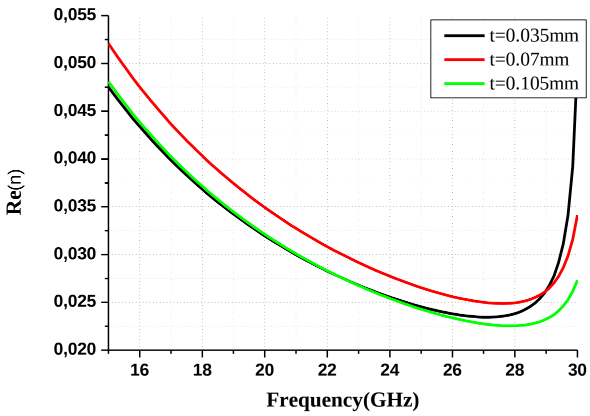
(a)

Figure III. 6: Effective permeability for different values of *d*: (a) Real part, (b) imaginary part.

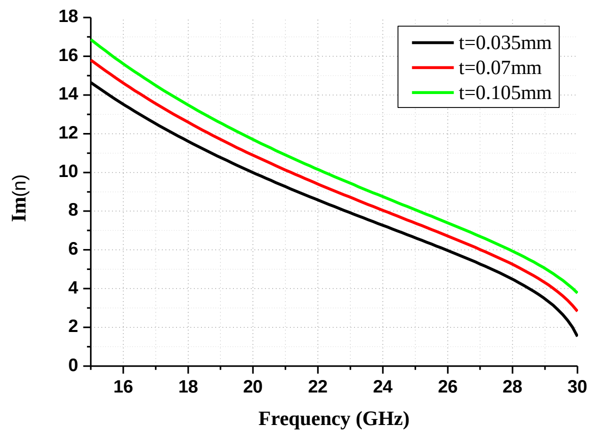
III.3.3.2 Effect of the metallization thickness "t''

In this section we study the influence of the conductor metallization thickness t on the electromagnetic properties of the metamaterial. First, we have fixed the substrate thickness at $d = 0.941$mm and conductor width $w = 0.15$ mm to ensure a plasma frequency of 22 GHz, suitable for a positive permittivity and a ultra-refraction region ($0<n<<1$) in the operating frequency band [15-30 GHz]. Secondly, we chose for the metallization thickness t standard values available in the market: 0.035 mm, 0.070 mm or 0.105 mm.

We use the Fresnel inversion method to obtain the constitutive parameters (ε_{reff} and μ_{reff}) and the refraction index of the metamaterial.



(a)

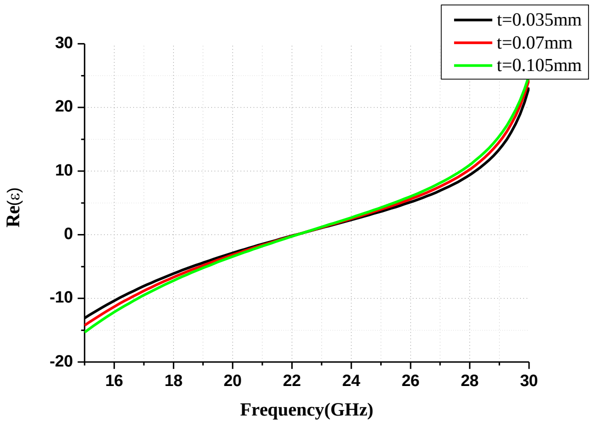


(b)

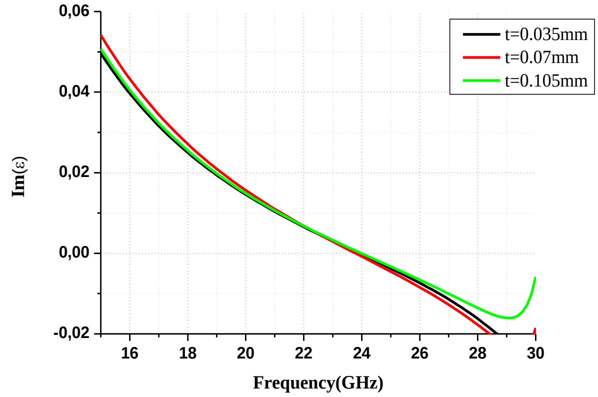
Figure III. 7: Refractive index n for different values of t: (a) Real part, (b) imaginary part.

As we can see in (Figure III. 7) that the real part of refractive index (n) in our cell cross type metamaterials is positive and close to zero in operating zone [15GHz – 30 GHz].

And the imaginary part of the index (n) is greater than zero almost all analyzed frequency.



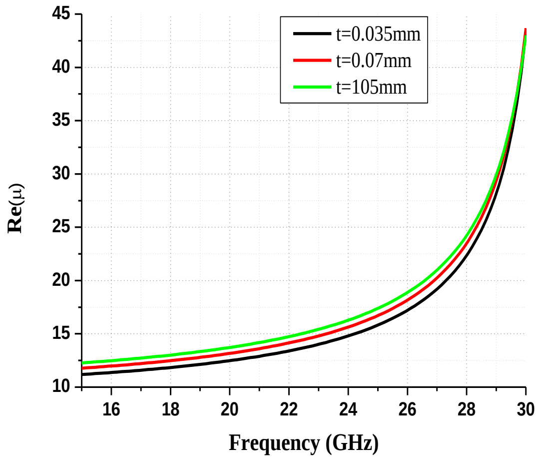
(a)



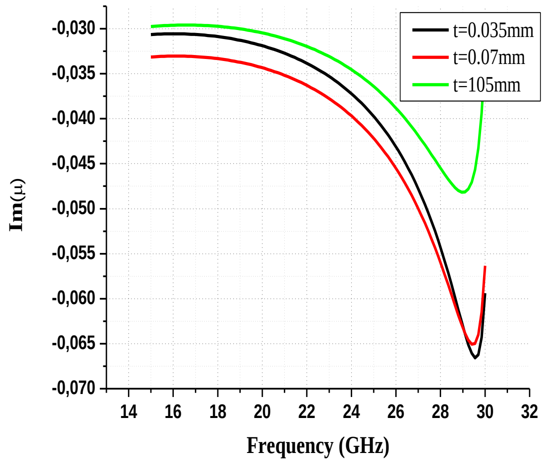
(b)

Figure III. 8: Effective permittivity for different values of t: (a) Real part, (b) imaginary part.

In this figure we study the permittivity real and imaginary part, the real part we seen in our travel frequency 22GHz Its value is equal zero we named Frequency Plasma the part before 22GHz are negative and the part after travel frequency is positive exactly as we want . And when the value of thickness t=0.035mm the frequency plasma exactly equal zero. And the imaginary part of the permittivity is greater than zero almost all analyzed frequency.



(a)

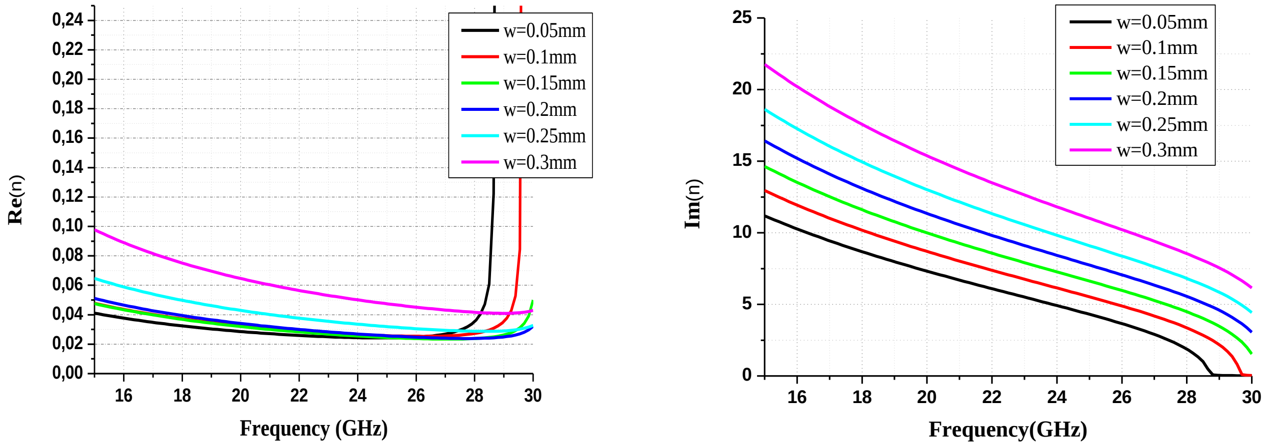


(b)

Figure III. 9: Effective permeability for different values of t: (a) Real part, (b) imaginary part.

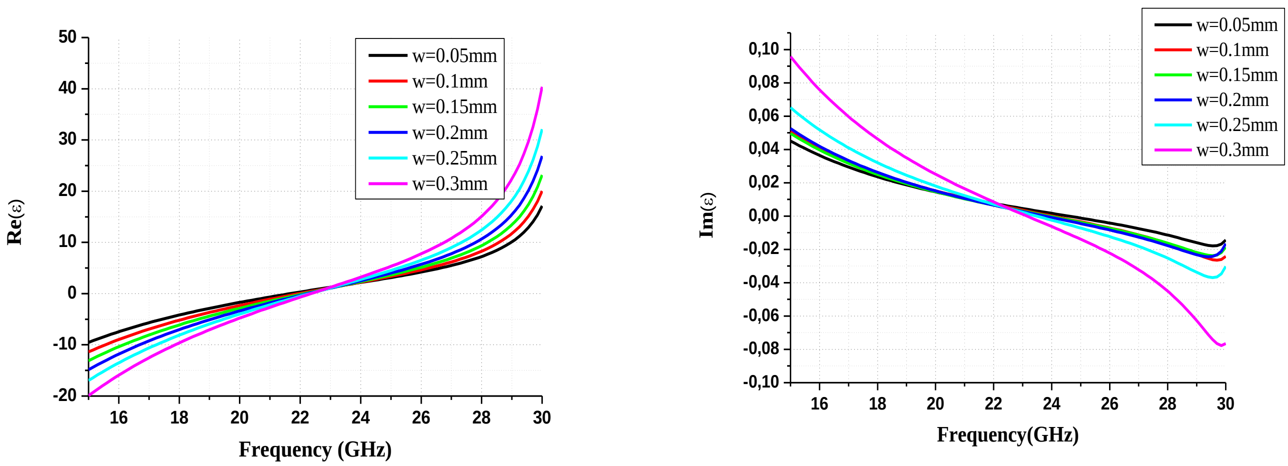
III.3.3.3 Effect of the width "*w*":

In this section, we study the influence of the conducting width 'w' on the electromagnetic properties of the metamaterial. for that, we fix the other unit cell parameters to: t = 0.035 mm and d = 0.941 mm. We vary w from 0.05 mm to 0.3 mm with a step of 0.05 mm



(a) (b)

Figure III. 10: Refractive index *n* for different values of *w*: (a) Real part, (b) imaginary part.



(a) (b)

Figure III. 11: Effective permittivity for different values of w: (a) Real part, (b) imaginary part.

The metamaterial plasma frequency is less sensitive to the conductor widths that to the substrate thicknesses, as it can be seen from (Figure III. 11). When w increases from 0.05 mm to 0.3 mm, the plasma frequency varies from 22to 24 GHz. The real part of the refraction index increases when we decrease the conductor width w, as it can be shown in (Figure III. 10). We observe also that, for *w* greater than 0.15 mm, the real part of the refraction index decreases, with the frequency in the lower region and present a valley where it is approximately constant, in the operating band 22-24 GHz. While it decreases continuously for *w* equal 0.15 mm.

Finally, we have fixed the entire unit cell geometrical parameters (*t*, *w*, and *d*) except the gap value *g*. These are: the metallization thickness *t* = 0.035 mm, the dielectric thickness *d* = 0.941 mm and the conductor width *w* = 0.15 mm.

III.4 The conventional patch antenna

As any microstrip antenna, the patch antenna is a single-layer design and consists of a radiating metallic patch, situated above of a thin dielectric substrate with a metallic ground plane situated on inside the substrate at the middle.

In this work the proposed antenna (Figure III. 12) is a copper patch placed on on Roggers RT/ duroid 5880 substrate (ε_r=2.2) at frequency 22GHz.

The core of the micro ribbon antenna is the conductor of the upper layer called patch. This patch can be considered as an open circuit transmission line of length *L* and width W, the currents becomes significant when the signal frequency is close to resonance. By considering only the fundamental mode for computations, the antenna resonance frequency is given by equation III.1

$$f_r = \frac{c}{2.(L_p+2.\Delta L_p)\sqrt{\varepsilon_{eff}}} \tag{III.1}$$

With:

c: Speed of light

ΔL_p: Length extension L

ε_{eff}: Effective permittivity

And its dimensions were obtained using the following equations:

The width of the patch is given by:

$$Width = \frac{C}{2\,f_r\sqrt{\frac{\varepsilon_r+1}{2}}} \tag{III.2}$$

W is the patch resonant width, *and* ε_r is the relative dielectric constant of the substrate (ε_r =2.2).

The patch resonant length is given by:

$$L = L_{eff} - 2 \times \Delta L \qquad \text{(III.3)}$$

Where

$$L_{eff} = \frac{c}{2 \times f_r \times \sqrt{\varepsilon_{reff}}} \qquad \text{(III.4)}$$

And the extension of the length (ΔL) is explained by the fact that the electric field does not suddenly stop at the edge of the patch but extends slightly. Its mathematical expression is as follows:

$$\Delta L = 0.412 \times h \times \left(\frac{\varepsilon_{reff}+0.3}{\varepsilon_{reff}-0.258}\right) \times \left(\frac{\frac{w}{h}+0.264}{\frac{w}{h}+0.8}\right) \qquad \text{(III.5)}$$

ε_{reff} is the effective dielectric constant.

h is the thickness of dielectric substrate.

ΔL stands for length extension.

And the value of ε_{reff} give up with this equation follows:

$$\varepsilon_{reff} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\left[\frac{1}{\sqrt{1+12\left(\frac{h}{w}\right)}}\right] \qquad \text{(III.5)}$$

After the application numeric we have this dimension:

Table III. 1: Antenna patch dimensions

	The calculated sizes for conventional antenna (mm)	The optimized sizes for conventional antenna (mm)	The approximated sizes for metamaterial antenna (mm)
L	3.94	3.6	3.5
Ls	25	25	25
W	5.39	5.3	5.5
W_s	20	20	20
h	0.914	0.914	0.914

Our antenna is feed by a slot. It seems that the slot coupling is the most suitable for the intended application. Indeed, it provides the following properties: high polarization purity, high efficiency, good directivity (Figure III.13)excellent bandwidth (Figure III.14).

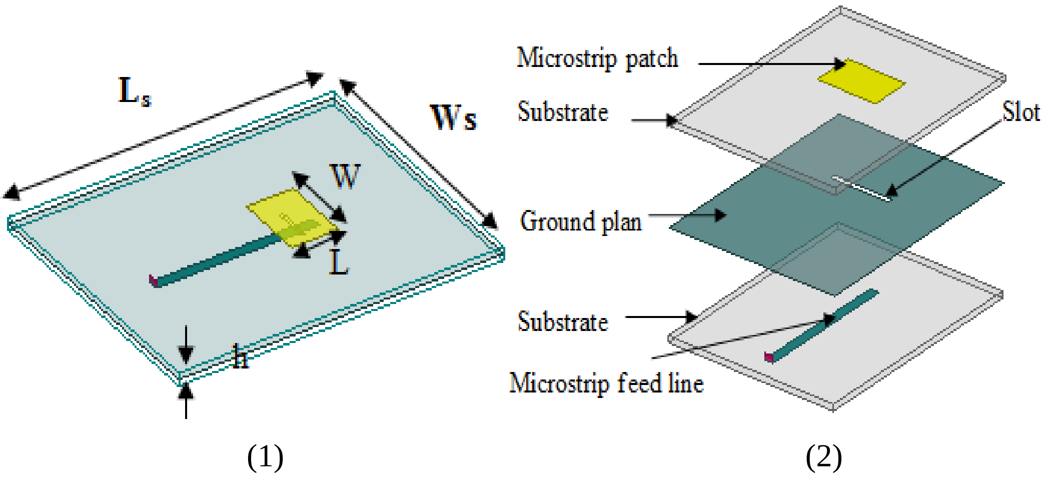


Figure III. 12: Microstrip patch antenna, (1) antenna geometry, (2) disassembled antenna structure.

III.5 Metamaterial patch antenna description

The metamaterial patch antenna realized by programmable cross grid type metamaterial through switches have two states, the state ON for the connected cross type with a refractive index close to zero, and the switches OFF state for the type disconnected which has a refractive index greater than 1, as explained in the description of the unit cell. The patch metallic part is made by the connected cross type and the space surrounded it is represented by the disconnected cross type. The dimensions of the metamaterial patch are approximately equal to that of conventional one, where *L* = 5.5 mm (11 times the period *a*) and *W* = 3.5 mm, (7 times *a*).

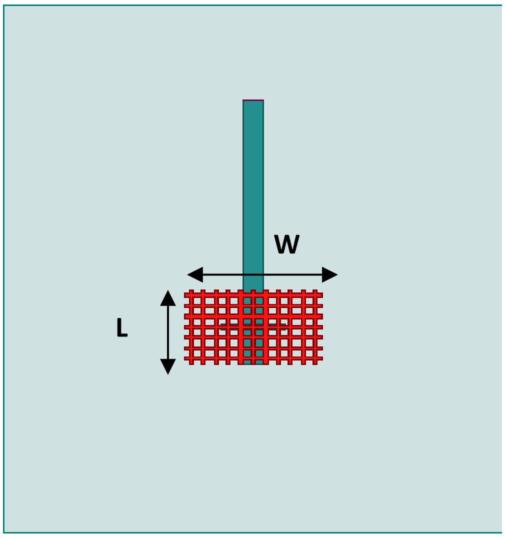


Figure III. 13: Metamaterial antenna without disconnected rows.

The (Figure III. 14) and (Figure III. 15) represent respectively the reflection coefficient and gain comparison between three antennas, which are the conventional antenna with optimized and approximated dimensions and the metamaterial antenna.

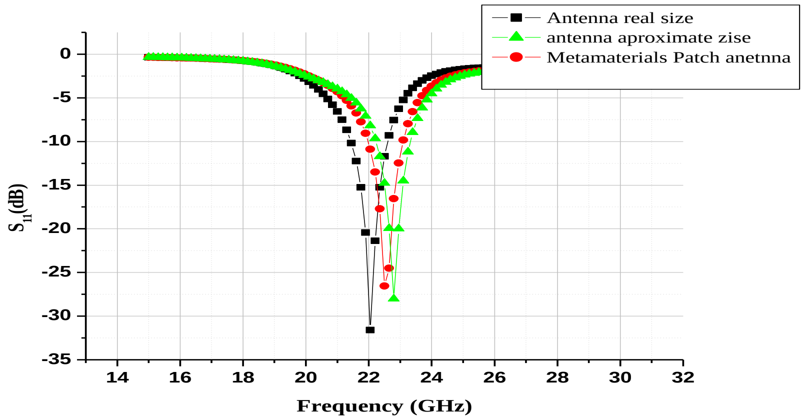
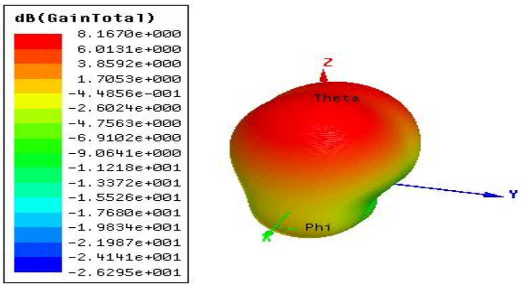
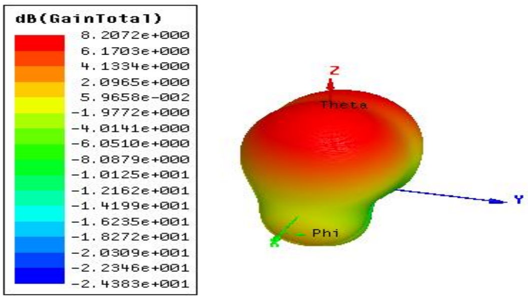


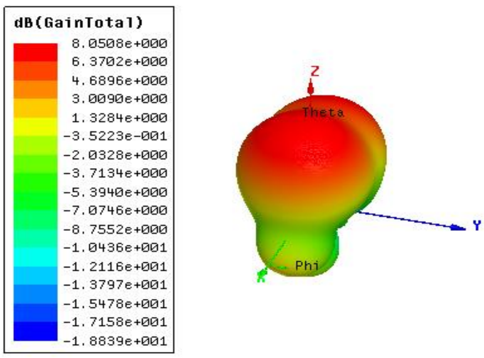
Figure III. 14: Comparison between the reflection coefficient $S_{11(dB)}$ of antenna with real size and antenna with approximates size and Metamaterials patch.



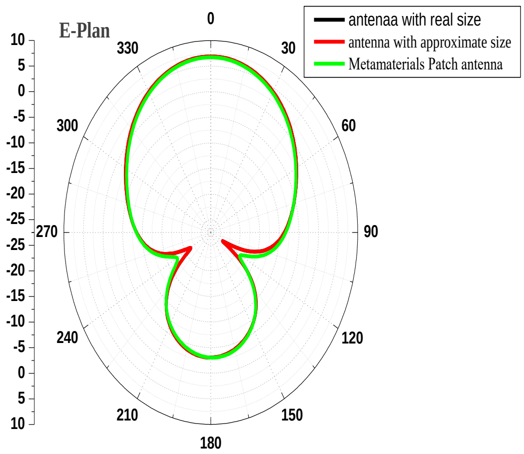
(a)



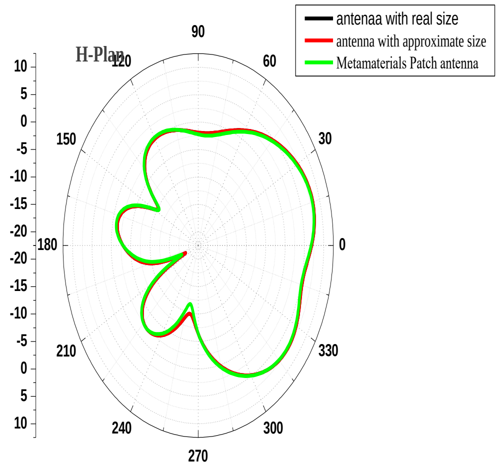
(b)



(c)



(d)



(e)

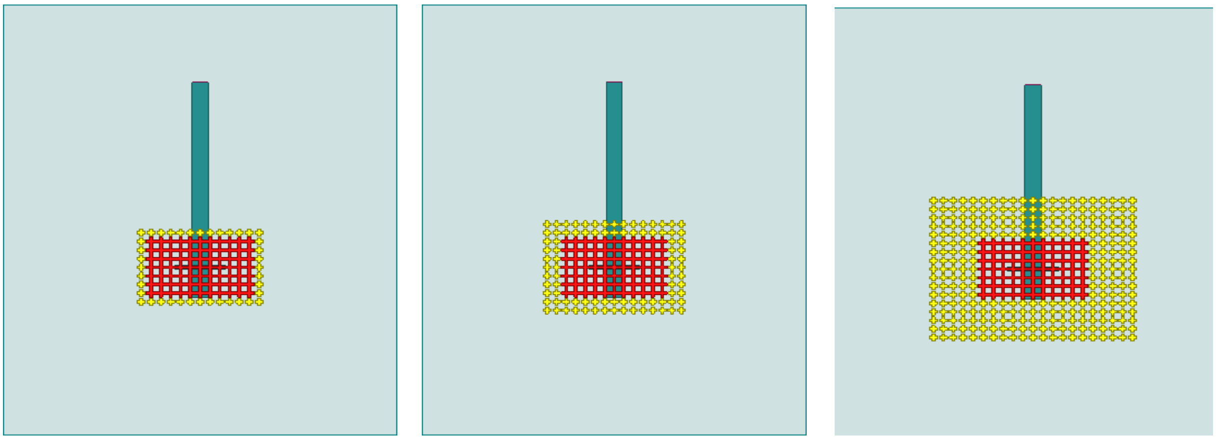
Figure III. 15: (a) Representation polar 3D of real antenna equal 8.17 dB; (b) Representation polar 3D of approximates antenna equal 8.20 dB; (c) Representation polar 3D of Metamaterial patch antenna equal 8.05 dB ;Comparison between representations Gain real and approximates and Metamaterials antenna patch (d) E-Plan (e) H-Plan.

In this figure we see that the antenna real has frequencies operates exactly at 22GHz and have the best adaptation by comparison with the two others. We note the same thing about the gain like, as shown in the (Figure III. 15). The antenna with optimized size gain is equal 8.17db and the antenna, with approximated size, gain is equal 8.20 dB. The metamaterial antenna exhibits approximately the same performances as the metallic patch antenna.

In this section we study the effect of disconnected metamaterial placed around the antenna radiating element on the antenna performences. We suround the radiating element by one two or fives rings of disonnected cross type metamaterial, as shwon in (Figure III. 16).

So we can say the result of one row or five gives the same result. The addition of the disconnectd type can leads to close the frequency operation to 22 GHz

As shows in (Figure III. 17), surrounding the antenna radiating element by disconnected cross type metamaterial affects slightly the antenna behavior. The operating frequency is lowered from 22.8 GHz to 22.35 Ghz. Adding one, two or fives rings of metamaterial round radiating element gives the same effect.



One row Two rows Five rows

Figure III. 16: The adding of the disconnected cells around the connected one effect.

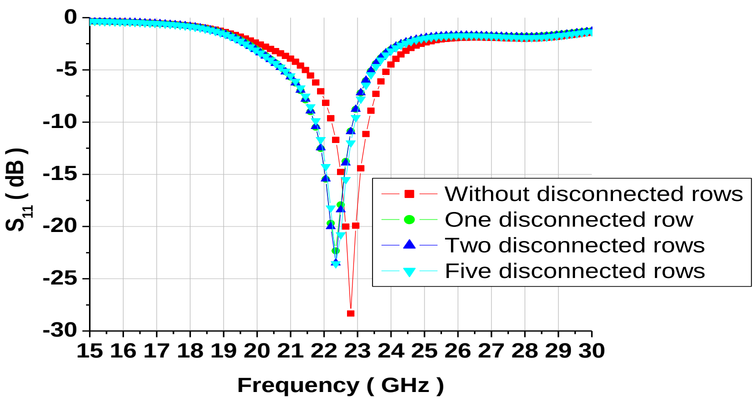


Figure III. 17: The coefficient reflection of the disconnected cells rows surrounding the connected one effect with these value: Without disconnected f= 22.8 GHz, One row f=22.35 GHz, Five rows f=22.35 GHz.

We summarized all the results of antenna we used in this dissertation in the table shown below

Table III. 2: Comparison between the cases of antenna

Cases	Frequency		Gain
	GHZ	dB	dB
Real antenna	22	-31.22	8.17
Approximate antenna	22.5	-26.55	8.20
Antenna without rows	22.8	-28.02	8.05
One row	22.35	-22.71	7.9996
Two rows	22.35	-23.05	7.9996
Five rows	22.35	-24	7.9996

According this result, we can say that adding disconnected type brings us closer to the working frequency, and we can also say that the number of rows after the first row does not matter. Results obtained with one or five rows are the same.

The antenna operating frequency is inversely proportional the rout-square of it's length L, as expressed by the equation III.1. Note the antenna width "W" doesn't affect the operating frequency. Our metamaterial agile antenna operates in a frequency band lying from f_{min} to f_{max}. This band is centered on $f_0 = \frac{f_{min}-f_{max}}{2}$is obtained by setting the antenna width and length to (W_0, L_0). For the metamaterial antenna the length L_0 is equal to 7 times the period "*a"*. In order to control the antenna operating frequency and to introduce the frequency agility, we have to change the antenna length L, this is achieved as follow:

1- By lowering the antenna length $L<L_0$, we increase the antenna operating frequency above the central frequency f_0
2- By increasing the antenna length $L>L_0$, we decrease the antenna operating frequency below the central value f_0.

Now for the two situations, L=7 times "*a"* or 9 times "*a"*, if we remove parts of the metallization in the y direction of the patch, the operating frequency changes proportionally to the removed metallization. The metallization is removed by steeps of two unit cells; one from each side of the patch, as shown in (Figure III. 18) in our metamaterial agile antenna the metallization is removed simply by acting on the unit cell switches (ON/OFF) to flip the metamaterial behavior from conducting to dielectric medium.

The metamaterial surface used to design our metamaterial agile antenna consists in an matrix arrangement of 9 unit cells, in the x-direction, by 13 unit cells in the y-direction. Each unit cell is represented by two numbers corresponding to the intersection of the line and row numbers in the matrix and noted C (n_x, n_y). The meta-surface lies from C (1,1) to C(9,13).

To set the antenna operating at the center frequency f_0 (L0 = 7 times *a*, W = 11 times *a*), we program cells C(n_x, n_y), where n_x is equal 2 and 8 and n_y variating from 2 to 12, to behave as conducting material and all the others cells to behave as dielectric material.

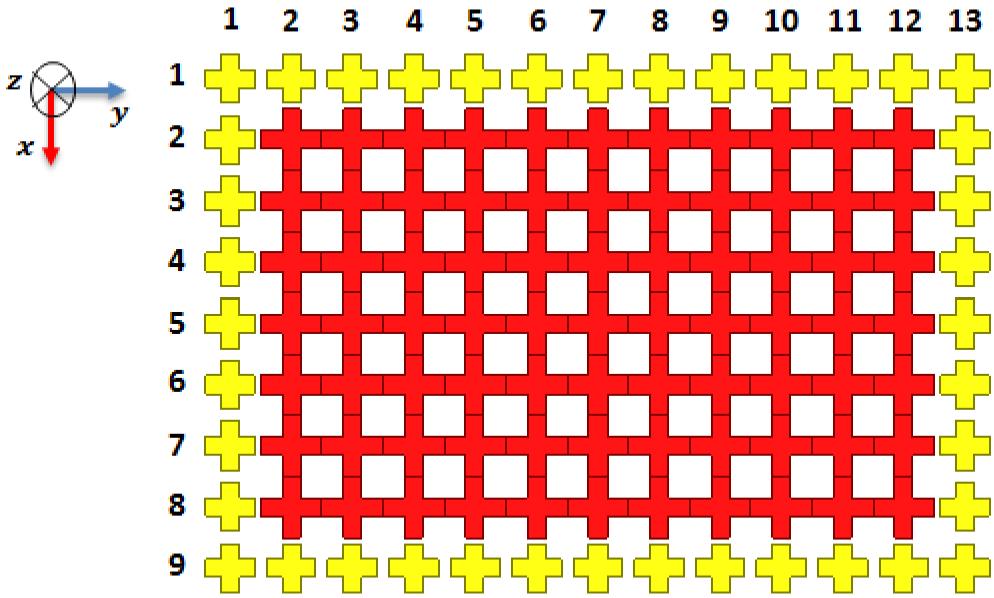


Figure III. 18: Matrix of meta-surface cells makes up the agile antenna

III.5.1 Controlling operating frequency above the central frequency f>f_0

To operate above the central frequency (f_0< f <f_{max}), the antenna radiating element, made by cells programmed as connected cross type metamaterial (conducting material) must be smaller than A_0 corresponding to L_0 =7 times *a*. To reach this goal, in a first step we remove metallization situated at line 1 and 9 (from row 2 to 12), to obtain an antenna length L= 7 times" *a"*. which correspond to the lower operating frequency in this range. In a second step, to control the agile antenna operating frequency above the central frequency, we remove metallization of cells situated at line 2 and line 8 simultaneously, and from row 2 to 12, to reach an antenna length L =5 times a, which correspond to the highest operating frequency in this range that is f_{max}.

Metallization is removed for two cells at one time (the first from the left and the second from the right side of the conducting area), as shown in (Figure III. 18). Removing metallization consists to flip the unit cell from connected type (conducting behaviors) to disconnected type (dielectric behavior) by acting on the switches (ON/OFF state) forming the unit cell. In table III.3, we report the size in mm of the removed metallization length and the corresponding number of removed cells represented by y_s.

Table III. 3: The slots dimensions for different cases

Cases	**Y_s**	
	(mm)	Cells
Case 1	0.5	1
Case 2	1.5	3
Case 3	2.5	5
Case 4	3.5	7
Case 5	4.5	9

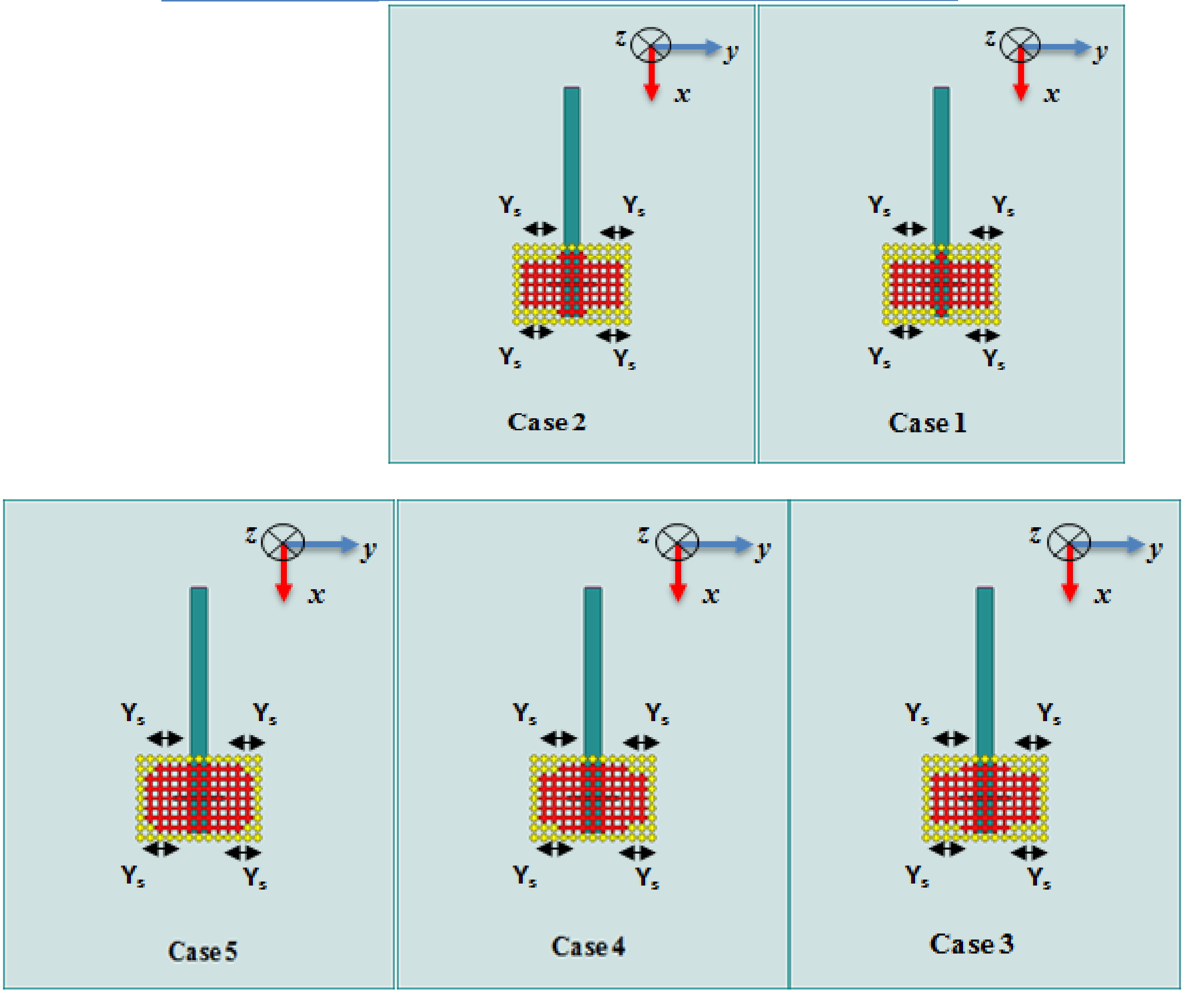


Figure III. 19: The cases of first proposition.

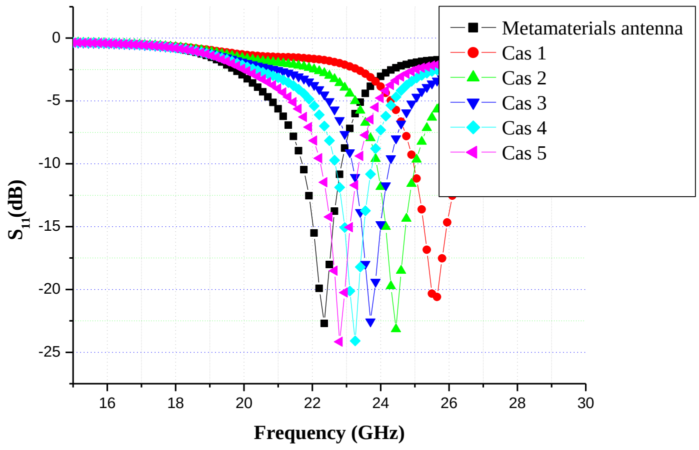
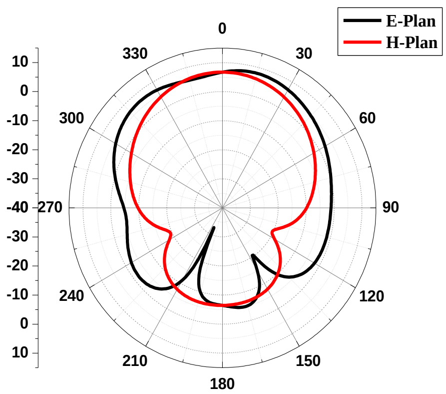
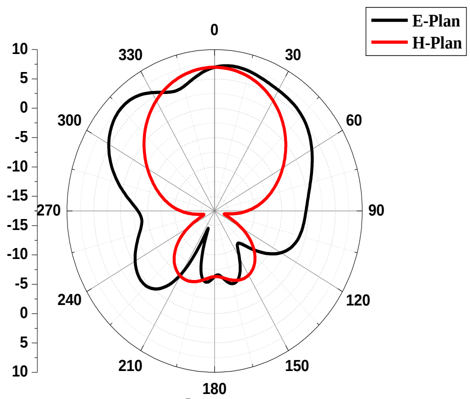


Figure III. 20: The reflection coefficient of the metamaterial patch antenna and the five cases.

We note that the operating frequency is tuned from 22.35 GHz, the mid band frequency, to f_{max} = 25.65 GHz, the maximal operating frequency (corresponding to case 1). From table III.4, We note that the metamaterial agile antenna gain remains slightly constant over all the frequency control range. It decreases by about less than 10% (from 8 to 7.3 dB). Note also, that the agile antenna is well matched for all the frequency range.



Metamaterials antenna



Case 1

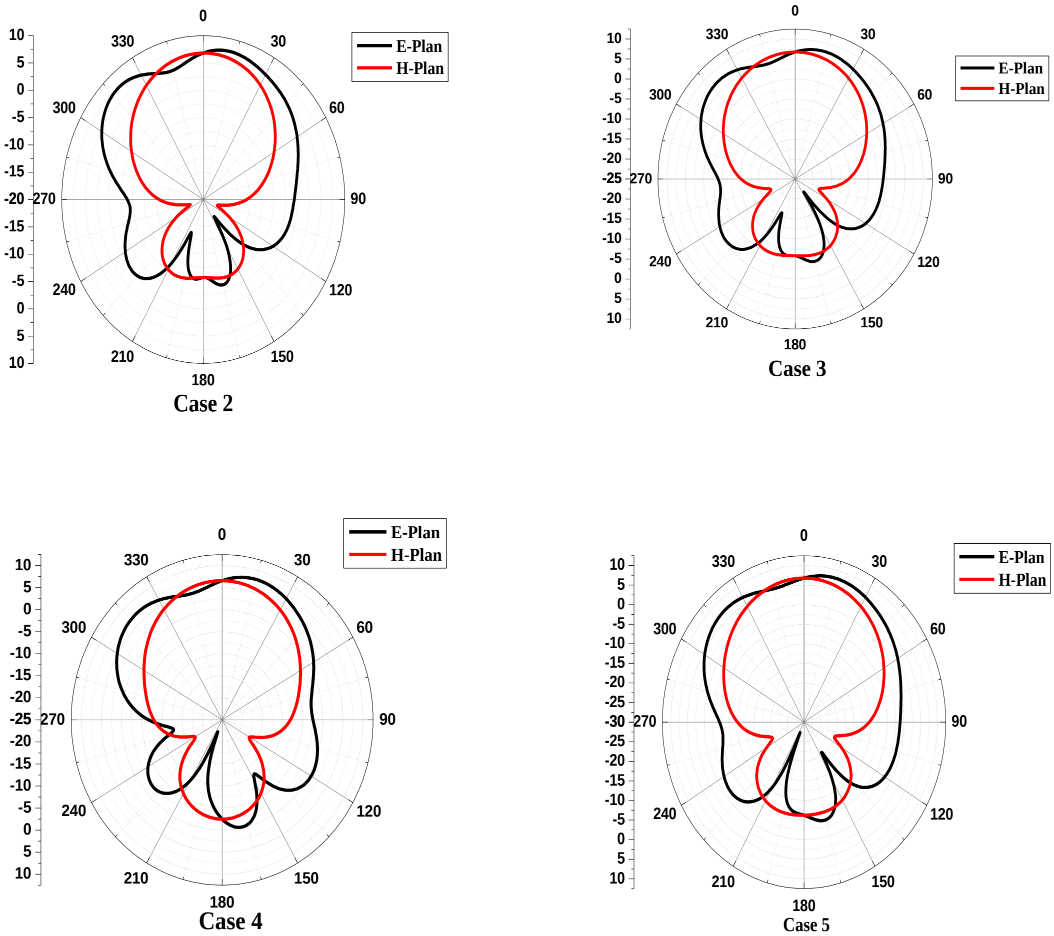


Figure III. 21: The polar gain representation of the metamaterial patch antenna and the five cases, for the H-plan and E-plan.

We summarized all the results in the table shown below

Table III. 4: Agile antenna operating frequency control above f_0

Case	Frequency (GHz)	S_{11}(dB)	Gain (dB)
Metamaterial antenna	22.35	-22.71	7.99
Case 1 Y_s=0.5mm	25.65	-20,60	7.3906
Case 2 Y_s=1.5mm	24.45	-24	7.6708
Case 3 Y_s=2.5mm	23.70	-23	7.8750
Case 4 Y_s=3.5mm	23.25	-24.10	7.9442
Case 5 Y_s=4.5 mm	22.8	-24.20	8.0506

III.5.2 Controlling operating frequency below the central frequency $f<f_0$

To operate below the central frequency ($f_{min}< f <f_0$), the antenna radiating element, made by cells programmed as connected cross type metamaterial (conducting material) must be greater than A_0 corresponding to L_0 =7 times "*a*". To reach this goal, in a first step we metallize all cells situated at line 2 and 9 (from colomn 2 to 12), to obtain an antenna length L= 7 times "*a*". Which correspond to f0 the highest operating frequency in this range.

To control the operating frequency below the central frequency, we remove metallization of cells situated at line 1 and line 9, simultaneously, and from colomn 2 to 12, to reach an antenna length L = 9 times "*a*", corresponding to the lower operating frequency in this range that is f_{min}. We remove metallization for two cells at one time one (from the left and right side of the conducting area), as shown in (Figure III. 22).

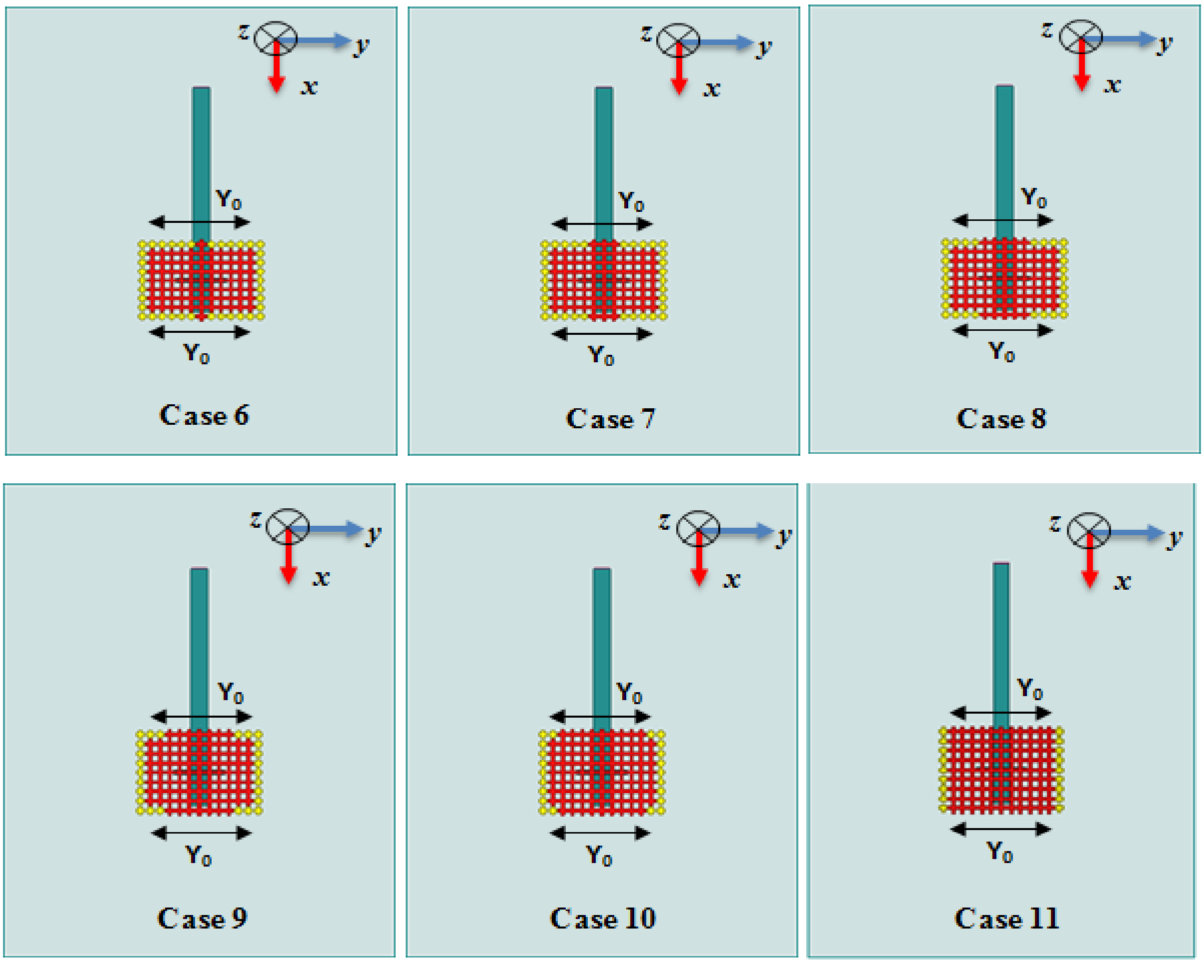


Figure III. 22: The cases of second proposition

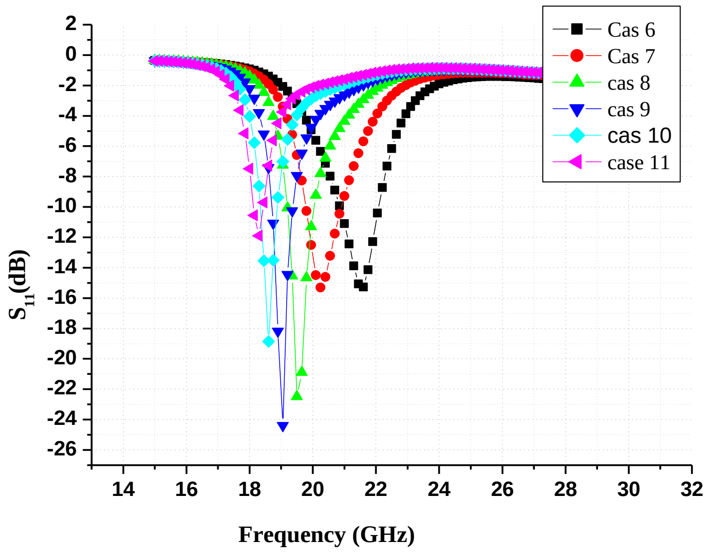
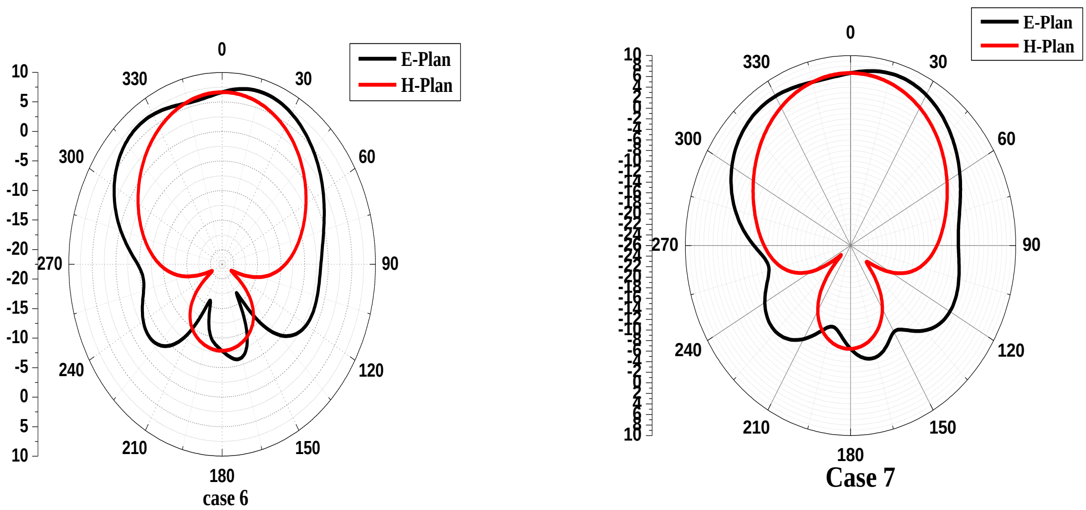
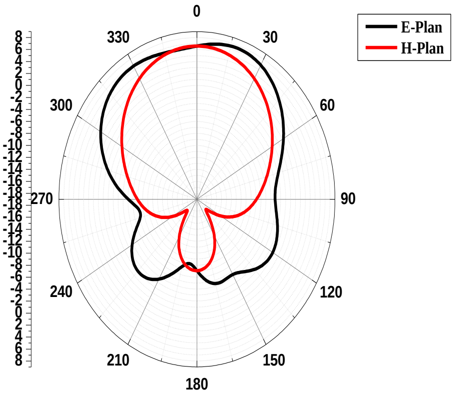


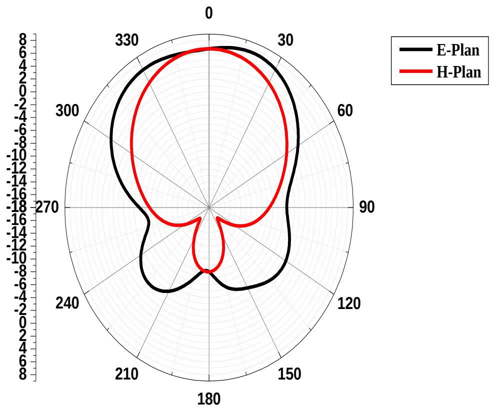
Figure III. 23: The reflection coefficient of the metamaterial patch antenna and the five cases

We note that the operating frequency is tuned from 21.60 GHz, slightly the mid band frequency, to the minimal frequency f_{min} = 18.29 GHz (corresponding to case 11). From table III.5, We note that the metamaterial agile antenna gain remains slightly constant over all the frequency control range. It decreases by about less than 12.5 % (from 8 to 7 dB). Note also, that the agile antenna is well matched for all the frequency range.

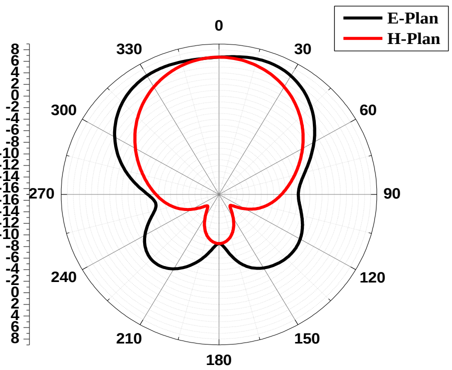




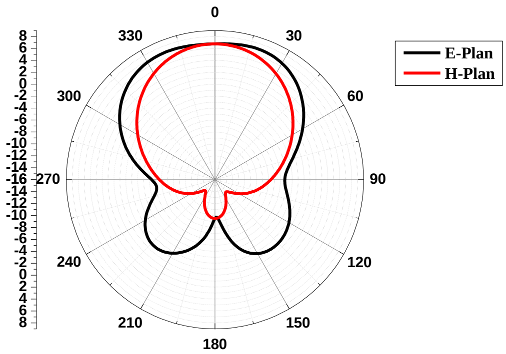
Case 8



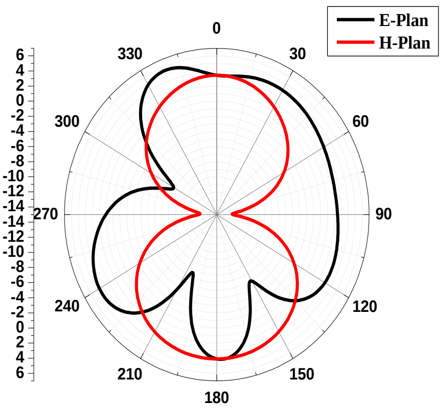
Case 9



Case 10



Case 11



All cross metamaterials connected

Figure III. 24: The polar gain representation of the metamaterial patch antenna and the cases, for the E-plan, and H-plan.

We summarized all the results in the table shown below

Table III. 5: Agile antenna operating frequency control below f_0

Case		Frequency (GHz)	S_{11}(dB)	Gain (dB)
Metamaterial antenna		22.35	-22.71	8
Case 6	$Y_0 = 0.5$ mm	21.60	-15.26	7.73
Case 7	$Y_0 = 1.5$mm	20.25	-15.40	7.74
Case 8	$Y_0 = 2.5$mm	19.50	-19.60	7.51
Case 9	$Y_0 = 3.5$mm	19.05	-24.45	7.42
Case10	$Y_0 = 4.5$mm	18.60	-18.90	7.24
Case 11	$Y_0 = 5.5$mm	18.29	-11.90	7.03

In (Figure III. 25), shows the overall operating frequency control of our metamaterial agile antenna. The operating frequency can be tuned from 18.6 GHz to 25.6 GHz with a resolution Δf equal to 0.5 GHz (0.35 GHz<Δf <0.75 GHz). The operating frequency control range is of 31.3 %, by a resolution of about 2%. In this frequency control range the overall antenna characteristics are slightly constant: good impedance matching and radiation gain greater than 7 dB.

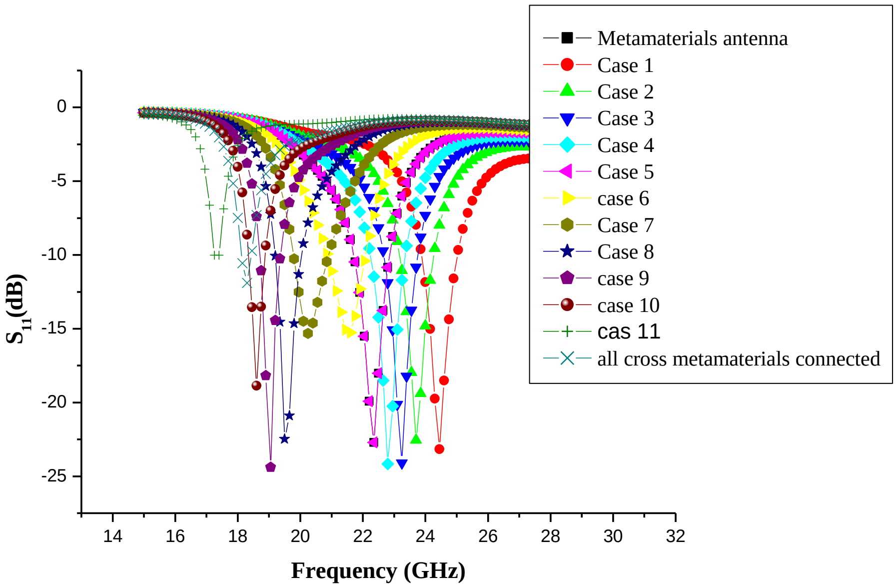


Figure III. 25: All interval of frequency of First and second proposition.

III.6 Conclusion

Our theoretical reference antenna is designed to operate at 22GHz. It presents an excellent gain equal to 8.17 dB and a good impedance matching with an reflection coefficient equal to $S_{11=}$-31.22 dB. Our proposed agile metamaterial antenna operates at 22.5 GHz and presents a gain of 8.20 dB. The shift in the operating frequency is due to the dimensional resolutions, dx in the x-direction, dy in the y- direction respectively, which are imposed by the period "*a*" of the metamaterial. In order to control the antenna operating frequency we modify the antenna radiating element length by changing some metamaterial unit cells behavior from disconnected cross type (dielectric behavior) to connected cross type (conducting behavior). Our proposed frequency agile metamaterial antenna design, presents an operating frequency control range of 31.3 %, by a resolution of about 2%. The frequency can be tuned from 18.6 GHz to 25.6 Ghz with a resolution df of about 0.5 GHz. In this frequency control range the overall antenna characteristics are slightly constant.

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General conclusion

General conclusion

In this work, we used agile metamaterial and we focused on introduce operating frequency agility. During the work carried out within the framework of this dissertation, we studied, optimized and characterized frequency agile metamaterial antenna, for multi standard telecommunications.

Frequency agile antennas are of primary importance in the context of configurability in the broad sense of a transmission / reception system. The underlying idea is to have an antenna which can control the operating point, that is to say the frequency at which the performance of the antenna is optimal

The first chapter; state of art of metamaterials we study the theoretical part of metamaterials and we present their principle fundamental proprieties with their field of applications in general and specially in the antenna domain.

The second chapter is about patch antennas and where we present technics of frequency agility.

The third chapter was dedicated to the study of two frequency agile antennas based on the metamaterials that we have characterized. In the first part, we characterize the metamaterial structure used to operate at a frequency of 22GHZ. The designed agile metamaterial unit cell can flip, by acting on an external electrical command system, between two different behaviors, the first one emulate an conducting medium and the second one an dielectric medium. The second part was dedicated to the study the proposed frequency agile metamaterial based antenna. The antenna frequency control range is about 31% of the central frequency of 22GHz by tuning step of 2%.

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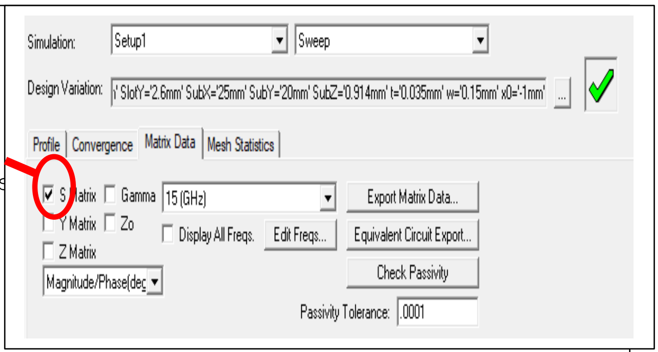
Annex

Calculation of the effective parameters by inversion of the fensel relation




```
function [mur,epsr]=Inv_Fresnel( S ,f , d );
%
% [mur,epsr] = Inv_Fresnel(S,f,d)
%
% mur : perméabilité relative, dim = 1xNfrequences
% epsr : permittivité relative, dim = 1xNfrequences
%
% S : paramètres S, dim = Nfrequencesx4
% S11 := Smatrix(:,1)
% S12 : = Smatrix(:,2) ...
% Skl : = Smatrix(:,Nports*(k-1) + l)
%
% f : vecteurs des fréquences, en Hz, dim = Nfrequencesx1
% d : épaisseur de matériaux
% ************dimensionnement des matrices utilisées***************
f=f';
N = size(f,1);
S11= S(:,1);
S21= S(:,3);
S12= S(:,2);
S22= S(:,4);

% *************** Calculs de T et de Gamma*************************
Coeff = ((S11.^2) - (S21.^2) + 1)./(2.*S11);
GammaPlus = Coeff + sqrt((Coeff.^2) - 1);
GammaMoins = Coeff - sqrt((Coeff.^2) - 1);
Gamma = GammaPlus;
% recherche de la racine de l équation du second degré possédant le
bon signe ****
for k=1:N;
if abs(GammaMoins(k))<=1
Gamma(k)=GammaMoins(k);
end
end
R=Gamma;
T = (S21)./(1 - (S11).*Gamma);

%-------------- impedance et l indice de refraction effective---------
z = (R+1)./(R-1);
k=(i.*log(T))./d;
n = ((k.*3e8)./(2.*pi.*f));

%------------------ mur_eff et epsr_eff ------------------------------
mur=-conj(n.*z);
epsr=-conj(n./z);
%-------------------- tracer S11 et S12 ---------------------
figure

plot(f,20.*log10(abs(S12)),f,20.*log10(abs(S11)))
legend('S12','S11')
grid
%----------------------tracer epsr --------------------------------
figure
plot(f,real(epsr),f,imag(epsr))
grid
title('la partie reél et imaginaire epsr')
legend('real(epsr)','imag(epsr)')
%----------------------- tracer mur -----------------------------
figure
plot(f,real(mur),f,imag(mur))
```

ملخص

بشكل عام ، للهوائي خصائص ثابتة بعد تصميمه وتحقيقه. لا تتوافق هذه الميزة مع التقدم التكنولوجي الهائل المتمثل في ظهور تطبيقات جديدة بترددات مختلفة. في السنوات الأخيرة ، تم استخدام المواد الفوقية على نطاق واسع في تطبيقات الهوائيات.

من بين أهم تطبيقات المواد الكهرومغناطيسية الجديدة او المواد الخارقة في مجال الهوائي ، يمكننا أن نذكر تحسين أداء الهوائي والتقليل من حجمه. ومع ذلك، لا يزال التحكم في خصائص الهوائي يمثل تحديًا كبيرًا لاستخدام المواد الخارقة في مجال الهوائيات، ومن خلال الرغبة المتزايدة في دمج هذه التطبيقات في جهاز واحد، يجب أن يكون للهوائي خصائص مرنة لتلبية متطلبات البيئة. هذه الهوائيات معروفة ب"هوائيات قابلة لإعادة التشكيل". في هذا العمل، صممنا هوائيًا رشيقا قائمًا على المواد الدقيقة رشيقة التردد. مع الحفاظ على كل من الاستقطاب ونمط الإشعاع. ستتم عملية إعادة التشكيل ويتم تحقيق الشكل النهائي للهوائي المقترح بعد دراسة بارا مترية صعبة باستخدام برنامج محاكاة HFSS.

الكلمات المفتاحية: هوائي قابل لإعادة التشكيل - مادة خام - هوائي رشيق - رشاقة هوائي **.**microstrip

Abstract

Generally, an antenna has fixed characteristics after its design and realization. This feature is not in line with the huge technological progress represented by the appearance of new applications at different frequencies. In recent years, metamaterial have been widely used in antennas applications.

Among the most important metamaterial applications in the antenna field we can mention tne antenna performance enhancement and size reduction. However, control of antenna characteristics remains a major challenge of metamatrial use in the antenna domain. By the increasing desire to integrate these applications into a single device, the antennas must have flexible characteristics to meet environment demands. These antennas are known by reconfigurable antennas. In this work we designed a frequency agile metamaterial based microstrip smart antenna. While maintaining both polarization and radiation pattern. The reconfiguration process will be done and the final form of the proposed antenna is achieved after a hard parametric study, using HFSS Simulation program.

Key words: reconfigurable antenna - metamaterial - agile antenna - microstrip antenna agility

Résumé

Généralement, une antenne a des caractéristiques fixes après sa conception et sa réalisation. Cette caractéristique n'est pas en ligne avec l'énorme progrès technologique représenté par l'apparition de nouvelles applications à différentes fréquences. Ces dernières années, les métamatériaux ont été largement utilisés dans les applications d'antennes.

Parmi les applications de métamatériaux les plus importantes dans le domaine des antennes, nous pouvons mentionner l'amélioration des performances et la réduction de taille des antennes. Cependant, la maîtrise des caractéristiques des antennes reste un enjeu majeur de l'utilisation métamatriale dans le domaine des antennes: par la volonté croissante d'intégrer ces applications dans un même appareil, les antennes doivent avoir des caractéristiques souples pour répondre aux exigences de l'environnement. Ces antennes sont connues par des antennes reconfigurables. Dans ce travail, nous avons conçu une antenne intelligente à microruban à base de métamatériaux agile en fréquence. tout en conservant à la fois la polarisation et le diagramme de rayonnement. Le processus de reconfiguration sera effectué et la forme finale de l'antenne proposée sera obtenue après une étude paramétrique approfondie, en utilisant le programme de simulation HFSS.

Mots clés: antenne reconfigurable - métamatériau - antenne agile - agilité d'antenne microruban