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designe*

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It is wonderful for a person to strive for and achieve success, but it is even more beautiful to acknowledge those who contributed to that achievement.

I dedicate this success to myself first, and then to everyone who supported me in completing this journey. You have always been my pillar of strength.

To the one who supported me without limits and gave without compensation, to the one who taught me that life is a struggle and its weapon is knowledge and education, and to the one who instilled in me the virtues of morality. My first supporter in my journey and my strength after God,

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“To you dear mother”

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Dedication

I dedicate this modest work

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General introduction

Metamaterials are a relatively new and emerging field of study that offers exciting opportunities to develop materials with custom-designed optical, mechanical, acoustic, or electrical functionalities. This is typically achieved by tailoring the constituent material architecture from the macro to the nanoscale. These structures can be constructed in two- or three-dimensional repeating structural arrays based on the desired properties.

Research in the field of metamaterials has been successful in demonstrating exceptional properties such as negative refractive index, negative density, negative incremental stiffness, negative Poisson's ratio, negative thermal conductivity, and shape reconfigurability. Unlike normal materials, the properties of metamaterials are dictated by the physical structure of the artificial unit cells, often referred to as meta-atoms. Therefore, the properties of a metamaterial can be manipulated by changing either the design or arrangement of these meta-atoms. In doing so, functionalities of metamaterials, including their permittivity and permeability, can also be tailored. By controlling the size of the meta-atoms, the operating frequency range of metamaterials can also be tuned to achieve specific behavior [1].

In this work, we are interested in designing smart materials using metamaterial unit cells with two distinct behaviors.

To conduct the study, we utilized HFSS software (a simulation and professional modeling tool) along with MATLAB.

This work is divided into three chapters:

The first chapter is devoted to the state-of-the-art of metamaterials.

The second chapter presents smart materials and frequency selective surfaces, discussing their types and applications.

The final chapter investigates the behavior of the designed smart metamaterial supercell using HFSS simulation software.

Chapter I

Stat of art about Metamaterials

I. Stat of art about Metamaterials

I.1 Introduction

Metamaterials are artificial materials that can achieve electromagnetic properties that do not occur naturally, such as negative index refraction or electromagnetic cloaking. The theoretical properties of metamaterials were first described in the 1960s by electromagnetic cloaking, who focused on the purely theoretical (at the time) concept of negative index materials. His concept became a reality in the turn of the century.

In the context of telecommunication, metamaterials can be defined as engineered materials with artificially tailored electromagnetic properties that differ significantly from naturally occurring materials. These properties are achieved by meticulously structuring the material at the micro or nanoscale, often using periodic arrangements of tiny elements like metals, dielectrics, or even other metamaterials.

Instead of relying on the inherent properties of the constituent materials, metamaterials derive their unique characteristics from their designed structure. This allows for manipulation of electromagnetic waves in ways that wouldn't be possible with conventional materials.[2]

I.2 Historical points for Metamaterials

Throughout human history, the control of light, electricity and heat has evolved to become the cornerstone of various innovations and developments in electrical and electromagnetic technologies. Wireless communications, laser and computer technologies have all been achieved by altering the way light and other energy forms act naturally and how to manage them in a controlled manner. At the nanoscale, to control light and heat, matured nanostructure fabrication techniques have been developed in the last two decades, and a wide range of groundbreaking processes have been achieved. Photonic crystals, nanolithography, plasmonic phenomena and nanoparticle manipulation are the main areas where these techniques have been applied successfully and led to an emergent material sciences branch known as metamaterials. Metamaterials and functional material development strategies are focused on the structures of the matter itself, which has led to unconventional and unique electromagnetic properties through the manipulation of light—and in a more general picture the electromagnetic waves—in widespread manner. Metamaterial's nanostructures have precise shape, geometry, size, direction and arrangement. Such configurations are impacting the electromagnetic light waves to generate novel properties that are difficult or even impossible to obtain with natural materials. [3]

I.3 Definition of metamaterials

Metamaterials are artificial three-dimensional (3D) structures composed of periodic subwavelength metal/dielectric arrangement of unit cells with exact dimensions [4]. A metamaterial is volumetric and is intended to provide artificial permeability ($\mu\mu$) and permittivity ($\epsilon\epsilon$) with extremely powerful electromagnetic (EM) wave control capabilities [5], leading to exceptional EM properties, which are often provided via resonant effects managed by the geometry of the unit cells [6]. Metamaterials have been used in such applications as magnetic resonance imaging [7], sensors [8], and antenna systems (for gain enhancement and beam steering) [9]. For EM integration, bulky sizes, low efficiencies, complex fabrication process are some of the disadvantages of metamaterials. To overcome these disadvantages, the two-dimensional (2D) metamaterials, which are known as meta surfaces, have been developed. They have attracted increasing research and development over recent years due to their small size, larger bandwidth, high efficiency, ease of fabrication, and less lossy characteristics [10, 11, 12]. A meta surface (MS) is intended to manipulate the amplitude, phase, and polarization of incident EM waves. Traditional techniques achieve polarization control of EM waves through using the crystal optical activity and Faraday effect. The drawback associated with these techniques are narrow bandwidth and incident angle response, and the resulting devices are large in size [13]. Similarly, the conventional absorbers, which are used to achieve absorption of EM waves, are bulky, fragile and challenging to manufacture. Meta surfaces can be utilized to control the EM waves within one thin layer, leading to substantial advantages, such as low cost, and high degree of integration. They can be used in a wide spectrum of applications such as perfect lens [14], perfect absorbing [15], invisibility [16], light bending [17], and polarization conversion [18], to name but a few.

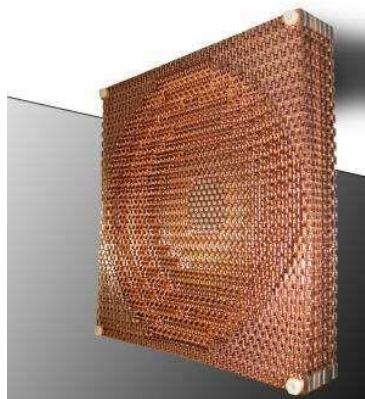


FIGURE I 1 STRUCTURE OF METAMATERIAL

I.4 Classification of Metamaterials:

Metamaterials can be classified based on their permittivity and permeability. These properties define their dielectric and magnetic responses. This classification divides metamaterials into four main categories: double positive, epsilon negative, mu negative, and double negative. Figure 1.4 presents a schematic of this classification.[19]

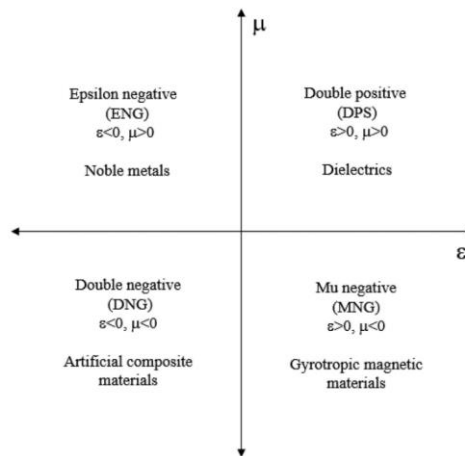


FIGURE I 2 CLASSIFICATION OF METAMATERIALS

I.4.1 Double positive (DPS) materials

DPS materials are natural, characterized by positive permittivity and permeability values simultaneously. Most dielectric materials exhibit these features and usually they are transparent to the incident electromagnetic waves and electric vector (E), magnetic vector (B) and the wave vector (k). They are also known as right-handed materials (RHMs).[19]

I.4.2 Epsilon negative (ENG) materials:

ENG materials are characterized by outstanding properties such as a negative refraction index, negative phase velocity, reverse Doppler effect and Cerenkov effect, among others. This category is composed of ceramic and polymer matrix composites, metals, doped semiconductors and plasmas. For microwave applications, the most common ENG materials are metal wires arranged as an infinite long parallel square matrix embedded into a dielectric medium. The electromagnetic wave propagation in this case is similar to the propagation in plasma. The permittivity of these materials is negative at frequency $\omega < \omega_p$, where ω [19]

I.4.3 Mu negative (MNG) materials

This group comprises composite materials with negative permeability. As materials with one negative parameter only, they are also known as single negative (SNG). Some natural materials such as ferrites present these characteristics. Since MNG materials show remarkable

behavior, they have been developed for artificial structures as resonators (split-ring resonators (SRRs), spiral resonators (SRs), S- and Ω -shaped resonators). SRRs can present circular or square geometry and they are characterized as a high conductive resonant structure. The unit cells for a SRR with circular and square geometry is presented in figure I.3 [19]

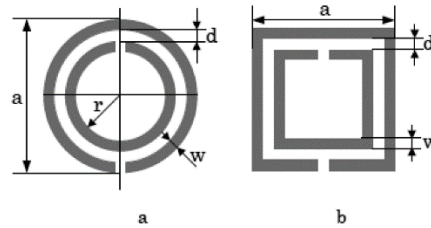


FIGURE I 3 UNIT CELL FOR MNG MATERIAL. CIRCULAR GEOMETRY (A) AND SQUARE GEOMETRY (B)

I.4.4 Double negative (DNG) materials

DNG materials do not have a natural formation; they are artificially developed to display negative permittivity and permeability simultaneously. They were initially reported theoretically by Veselago in 1968 and named left-handed media. According to their properties, DNG materials are also known as negative-index materials (NIMs) or backward (BW) media. Materials with these characteristics can be developed by using small scatterers, composed of metallic or magnetodielectric materials. This is the most interesting metamaterials category, since by attending to these characteristics, different media for several applications can be developed. DNG materials can be mainly composed of three structures: thin wires and SRR, transmission lines or mushroom structures. The combination of thin metal wires and SRR is the most commonly employed structure and is shown in figure I.4 [19]

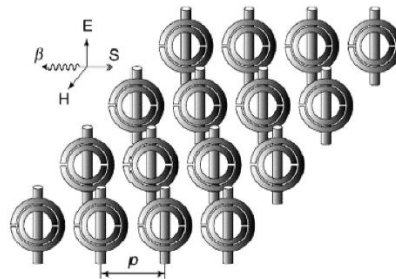


FIGURE I 4 DNG MATERIAL STRUCTURE COMPOSED OF THIN WIRES AND A SPLIT-RING RESONATOR (SRR)

I.5 Metamaterials Analytical Models

I.5.1 Drud model

Pendry theoretically demonstrated the concept of an artificially negative permittivity using a model where a metallic wire represents a plasma with negative permittivity [19']. This model is known as the Drud model.

The metal thin wire medium, whose unit cell is presented in figure 1.5 (b), exhibits a plasmonic type permittivity frequency function of the form:

$$\varepsilon_{\text{reff}}(\omega) = 1 - \frac{\omega_{pe}^2}{\omega^2 - j\Gamma_e\omega} \quad (1.1)$$

Analytic procedure is detailed in [19'] from which the Drude parameters ω_{pe} and Γ_e are expressed in function of the geometric dimensions (the period a and the radius of the wire r) as:

$$\omega_{pe} = \sqrt{\frac{2\pi c^2}{a^2 \ln(a/r)}} \quad (1.2)$$

$$\Gamma_e = \varepsilon_0 \left(\frac{a\omega_{pe}}{\pi\sigma r^2} \right) \quad (1.3)$$

Where c is the speed of light and σ the conductivity of the metal. We observe from (1.1) that $\text{Re}(\varepsilon_{\text{reff}}) < 0$ for $\omega < \sqrt{\omega_{pe}^2 - \Gamma_e^2}$.

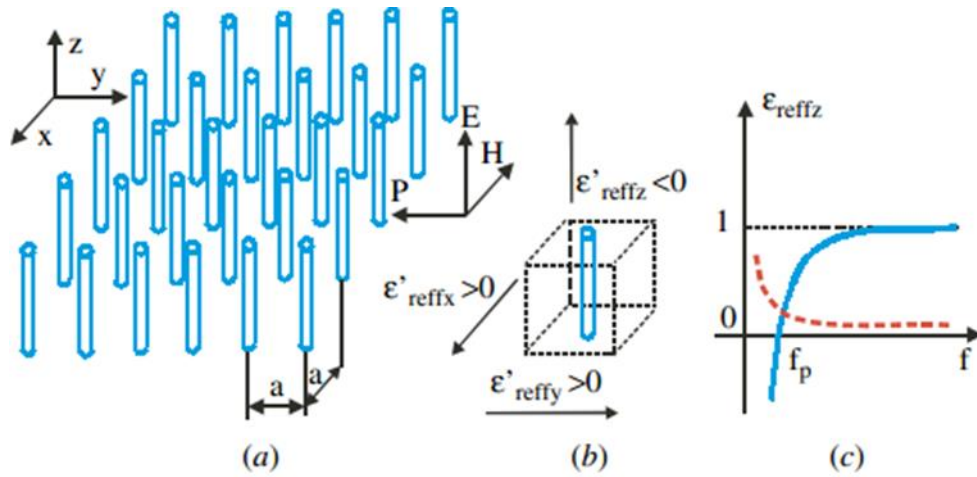


FIGURE I 5 (A) 2D THIN WIRES ARRANGEMENT, (B) THIN WIRE UNIT CELL, AND. (C) REAL (SOLID BLUE) AND IMAGINARY (DASHED RED) PARTS OF EFFECTIVE PERMITTIVITY OF METAMATERIAL

I.5.2 Lorentz model

The SRR in figure 1. 6-(b) exhibits a permeability frequency response of the form [19']

$$\mu_{\text{refff}}(\omega) = 1 - \frac{\omega_{pm}^2}{\omega^2 - \omega_{0m}^2 + j\Gamma_m\omega} \quad (1.4)$$

This model is known as the lorentz model.

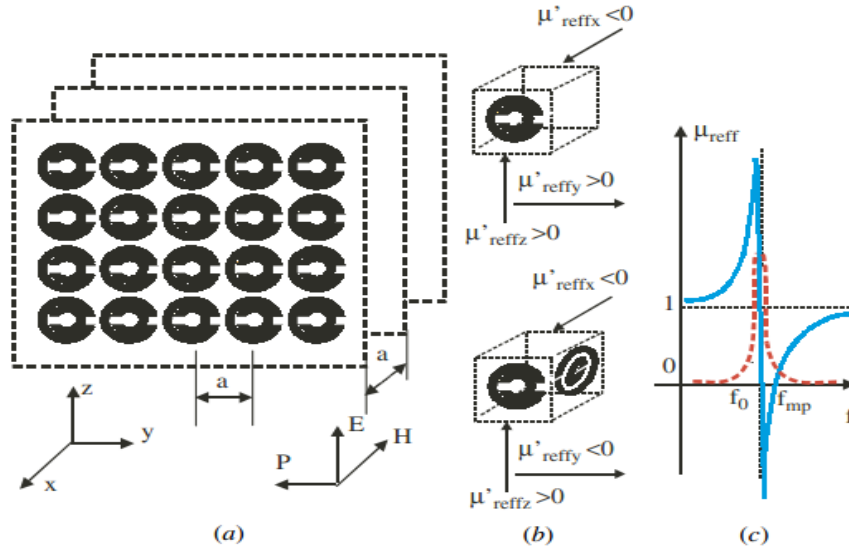


FIGURE I 6 (A). ARRAY OF SRR. (B). SRR OF 1D AND 2D UNIT CELLS (C). $\text{RE}(\mu_{\text{reff}})$ (SOLID BLUE), $\text{IM}(\mu_{\text{eff}})$ (DASHED RED).

I.6 Metamaterial applications

I.6.1 Metamaterial as antenna

Metamaterials have become a game-changer in antenna design, offering exciting possibilities compared to traditional antennas. Here's a breakdown of how they're impacting the field:

Miniaturization: Metamaterials can significantly reduce the size of antennas. This is particularly beneficial for applications where space is limited, like mobile devices or wearable electronics.

Enhanced Gain: By manipulating the electromagnetic properties of metamaterials, antennas can achieve higher gain, meaning they can focus and transmit electromagnetic waves more efficiently in a specific direction.

Wider Bandwidth: Metamaterials can broaden the operating frequency range of antennas, allowing them to function effectively across a wider spectrum.

Beam Steering: The design of metamaterials can be used to control the direction of the radiated beam from the antenna, enabling dynamic beam steering functionalities. [20]

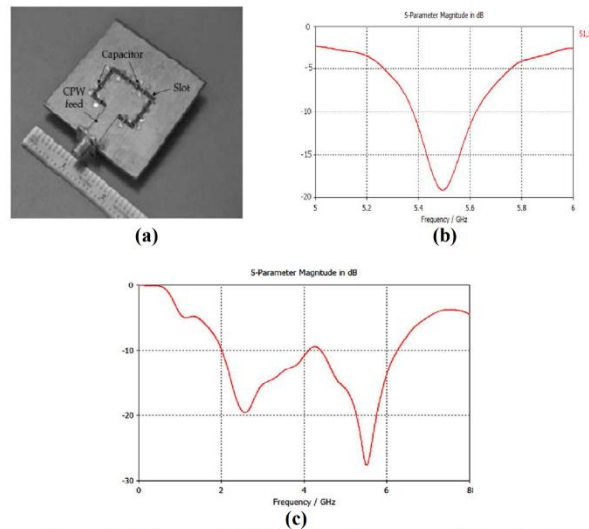


FIGURE I 7 (A) 3D IMAGE OF CPW FEEDING OF AN ANTENNA (B) RESULT OF SIMPLE PATCH ANTENNA (C) RESULT OF METAMATERIAL ANTENNA.

I.6.2 Metamaterial as Absorber

Metamaterial absorbers are a fascinating application of metamaterials in the field of electromagnetics. They are engineered materials designed to efficiently absorb electromagnetic radiation, such as light or radio waves.

Unlike traditional absorbers that rely on inherent material properties, metamaterial absorbers achieve their exceptional absorption through meticulously designed structures. These structures, often periodic arrangements of subwavelength resonators, can manipulate electromagnetic waves in unique ways.

Radar Absorbing Materials (RAM): Metamaterial absorbers can be used to create stealth materials that minimize radar detection of objects.

Solar Cell Efficiency Enhancement: They can be incorporated into solar cells to capture more light and improve energy conversion efficiency.

Electromagnetic Interference (EMI) Shielding: Metamaterial absorbers can be used to shield electronic devices from unwanted electromagnetic interference.

Thermal Management: By absorbing specific wavelengths of light, metamaterials can be used for thermal management applications.

Research in this field is ongoing, with scientists exploring novel designs for even more efficient and versatile absorbers. This could lead to applications in areas like:

Perfect Absorbers: The development of metamaterials that achieve near-perfect absorption across a broad spectrum.[20]

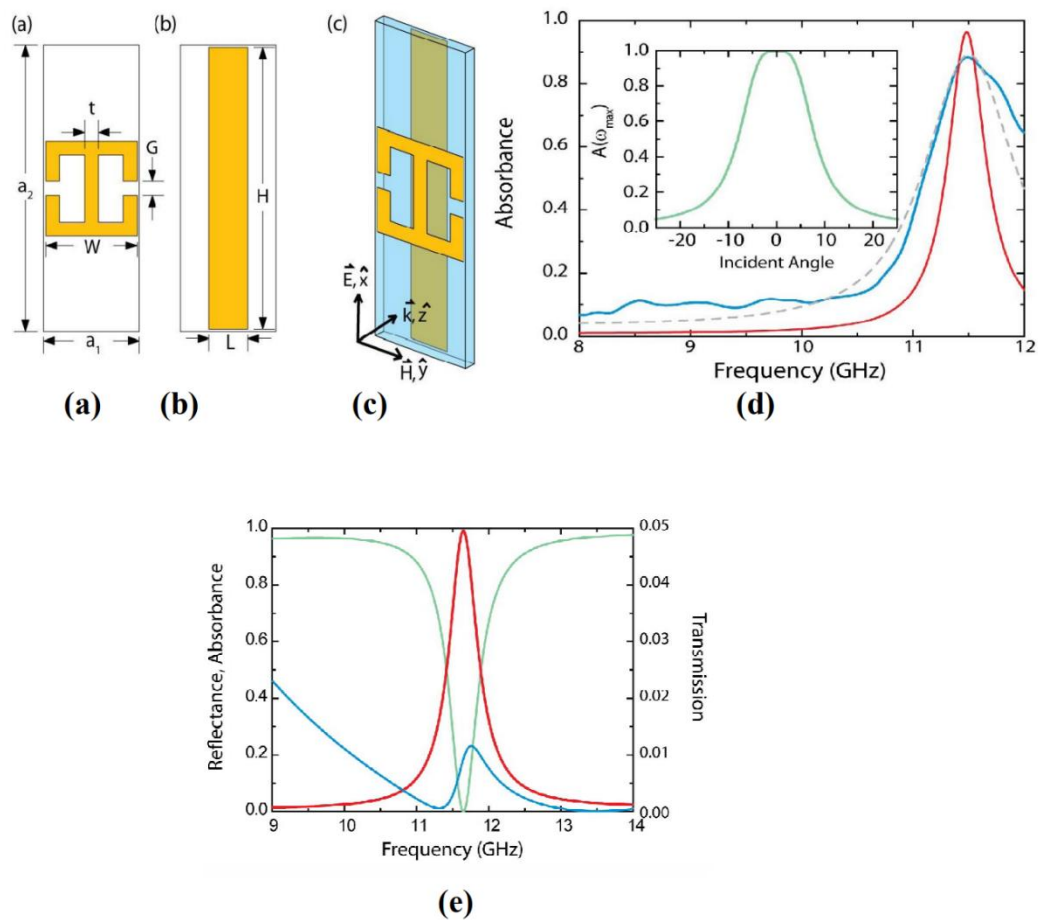


FIGURE I 8 (A), (B)&(C) THE UNIT CELL IS SHOWN WITH ITS COMPONENT (D) RESULTS AFTER FABRICATION (E) RESULTS AFTER SIMULATION.

I.6.3 Metamaterial as super lens

Metamaterials have revolutionized the field of optics by enabling the creation of super lenses – a technology with the potential to break the diffraction limit. Here's how these fascinating materials are pushing the boundaries of what we can see:

Conventional lenses are limited by the diffraction limit, a fundamental principle that restricts the ability to focus light beyond a certain point. This limitation arises from the wave nature of light and becomes more pronounced for shorter wavelengths like visible light. As a result, traditional lenses struggle to resolve features smaller than half the wavelength of light they interact with.

Super lenses, crafted from meticulously designed metamaterials, defy the diffraction limit. These metamaterials possess exotic properties not found in nature, achieved through their unique nanostructures. Here's how they work:

Negative Refraction: Certain metamaterial designs exhibit negative refraction, a phenomenon where light bends in the opposite direction compared to conventional materials. This allows for the focusing of light beyond the diffraction limit, enabling the visualization of features smaller than the wavelength of light.

Evanescent Wave Amplification: Super lenses can manipulate evanescent waves, which are electromagnetic waves that decay exponentially with distance from their source. By cleverly engineering the metamaterial structure, these evanescent waves can be amplified and recovered, leading to superior resolution.[20]

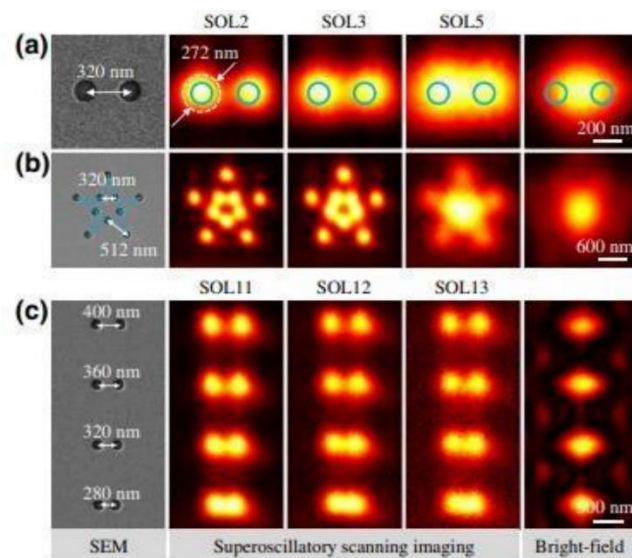


FIGURE I 9 ROWS (A-B) SHOWS IMAGING RESULTS WITH SUPEROSCILLATORY ILLUMINATION USING METAMATERIAL SUPERLENSES WITH DIFFERENT HOTSPOT SIZES OF THE FOCUS. ROW (C) SHOWS IMAGING RESULTS WITH SUPEROSCILLATORY ILLUMINATION USING METAMATERIAL SUPERLENSES WITH DIFFERENT

I.6.4 Metamaterial filters

A tunable metamaterial unit cell is the fundamental building block of a tunable metamaterial. It's a single, engineered structure designed to have its electromagnetic properties adjusted after its initial fabrication. This allows for dynamic control over how the metamaterial interacts with light and other electromagnetic waves.

Tunable metamaterial filters are a revolutionary class of filters that leverage the unique properties of metamaterials to achieve dynamic control over light filtering. Unlike conventional

filters with fixed properties, these filters offer the ability to adjust their filtering behavior on demand.[21]

The key to a tunable metamaterial filter lies in its tunable unit cell, the fundamental building block of the filter. This unit cell incorporates mechanisms that allow for adjustments to its properties after fabrication.

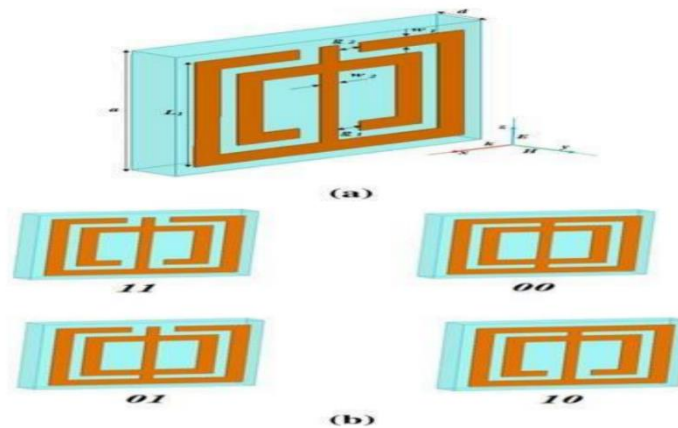


FIGURE I 10 (A) TUNABLE METAMATERIAL UNIT CELL, (B) ALL DIFFERENT CASES OF THE GAPS

I.6.5 Metamaterials based smart materials:

Metamaterials are engineered materials with the potential to revolutionize the field of smart materials. Unlike traditional materials with fixed properties, metamaterials offer a unique advantage: their properties can be tailored through design, making them highly responsive to external stimuli. This tunability unlocks exciting possibilities for creating smart materials with dynamic and adaptable functionalities.

Traditional smart materials exhibit a change in one or more properties (e.g., electrical conductivity, shape) in response to external stimuli like light, temperature, or electric fields. Metamaterials, with their ability to possess exotic electromagnetic properties, can be designed to interact with these stimuli in unique ways. This opens doors for creating smart materials with:

Enhanced Sensitivity: Metamaterial designs can amplify the response of a smart material to external stimuli, leading to more pronounced property changes.

Multi-Functionality: By incorporating different functionalities within the metamaterial structure, smart materials can be designed to respond to multiple stimuli simultaneously.

Reconfigurability: Tunable metamaterials can be used to create smart materials that can dynamically adjust their response based on the external environment... [21]

I.7 Conclusion:

Metamaterials are acting as a game-changer in the development of smart materials. Their unique ability to have properties engineered by design, rather than dictated by composition, opens doors for a new generation of responsive and adaptable materials. By combining metamaterials with traditional smart materials, researchers are creating materials with enhanced sensitivity, multi-functionality, and reconfigurability. From light-responsive fabrics to temperature-adapting structures and metamaterial sensors, the possibilities are vast. While challenges like precise fabrication and scalability remain, the future of metamaterial-based smart materials is brimming with potential to revolutionize various sectors and create groundbreaking advancements in technology.

Chapter II

Smart materials

II. Smart Materials

II.1 Introduction

Thousands of years ago humans used materials for different causes due to which there was an enhancement in their living standards. Even civilizations were divided on the basis of their discovery of materials like the first age was the Stone Age. The most revolutionary age was the Bronze Age because bronze was more durable and harder. The discovery of bronze was the beginning of new metallurgy era after that many materials discovered. From the past two decades, science and technology have made great improvements in synthesizing the new materials. They are divided mainly into four categories which are polymers, ceramics, metals, and smart materials. Among them, smart materials are becoming more popular because they have various applications as compared to standard materials. The special materials that can change their properties such as materials which can change its shape just by adding some heat or can change its phase instantly when placed near magnet are called smart materials. This new era of smart materials will have a great impact on mankind, for example, some of them can change their properties according to the environment and some of them have sensory capabilities some of them can repair automatically and some of them have self-degradation, these extraordinary capabilities of smart materials will have an impact on all aspects of civilization. Various smart materials already exist like piezoelectric materials, shape memory alloys, magneto-rheological materials, and electro-rheostat materials and many more to be discovered. This chapter concentrates on the introduction to different types of smart materials and their potential applications in various areas.[22]

During this chapter, we discussed an overview of smart materials in terms of their general definition, classifications, and various applications. and we discussed also about the frequency selective surface and their types and applications

II.2 Smart materials in general

"Smart materials" refer to those materials which have the ability to change their composition or structure, their electrical and/or mechanical properties, or even their functions in respond to some environmental stimuli like temperature, pressure, magnetic and electric fields, chemical, or nuclear radiation. Generally, "smart" materials are implanted in systems whose integral properties can be favorably altered in order to respond to the performance needs. The terms "smart" and "intelligent" are used interchangeably for these materials. Takagi defined intelligent materials as those which respond to different environmental changes at the most optimum conditions and manifest their own functions accordingly . The interest researchers

who were engaged in the subject of smart materials have been triggered by the plentiful examples of smart materials that were provided by nature. For example, the leaves of *Mimosa pudica* collapse suddenly when touched; leaflets of *Codariocalyx motorius* rotate under exposure to sunlight; sunflowers turn towards the sun; Chameleons change color according to environmental situations. Smart materials are usually utilized as actuators and sensors, and their associated "stimulus" and "response" is depicted in. Major advantages of smart material actuators and sensors include high energy density, fast response, compact size, and fewer moving parts. Some disadvantages include limited strain outputs, limited blocking forces, high cost, and sensitivity to harsh environmental conditions. The nonlinear properties of these materials present one of the major hurdles for their application. They are more likely to be observed as hysteresis. This nonlinear behavior is described in and among others. Recent progress in smart materials for distributed actuators and sensors has triggered a considerable interest in smart structures. Once smart materials are bonded to or embedded in conventional structures, those structures obtain sensing, actuating and processing or controlling capabilities, which are the basic active features of smart or intelligent structures.[23]

II.3 Types of smart materials

These materials with one or more property can be significantly altered in a controlled fashion by external stimuli. Thus, this material has built-in or intrinsic sensor (s), actuator (s) and control mechanism (s) by which it is capable of sensing a stimulus, responding to it in a predetermined manner and extent, in a short or appropriate time and reverting to its original state as soon as the stimulus is removed. There are a number of types of smart material available and some are discussed below.[24]

II.3.1 Piezoelectric materials

Piezoelectric materials are very common example of such materials where they produce a voltage when stress is applied. Since this effect also applies in the reverse manner, a voltage across the sample will produce stress within the sample. Suitably designed structures made from these materials can therefore be made that bend, expand or contract when a voltage is applied. They can also be used in optical-tracking devices, magnetic heads, dot-matrix printers, computer keyboards, high-frequency stereo speakers, accelerometers, micro-phones, pressure sensors, transducers and igniters for gas grills.[24]

II.3.2 Shape Memory Alloys (SMA)

Shape Memory Alloys or shape memory polymers, are materials that can hold different shapes at various temperatures. They can be deformed and returned to their original shape by heating. The most commonly available Shape Memory Alloy is Nitinol, which was originally developed by the Naval Ordnance Laboratory. SMA's have the ability to change phase as a function of temperature, and in that process generate a force or motion. They are capable of relatively high energy but move slowly. Typically, applications include morphing structures, thermal triggers, and some high strain energy absorbing applications. Advanced materials still under development include magnetically activated shape memory alloys. [24,25]

II.3.3 Magneto restrictive materials

similar to piezoelectric, respond to only magnetic fields rather than electric. They are typically used in low-frequency, high-power sonar transducers, motors and hydraulic actuators, along with the shape-memory alloy Nitinol, magneto restrictive materials are considered promising candidates for achieving active damping of vibrations. [24]

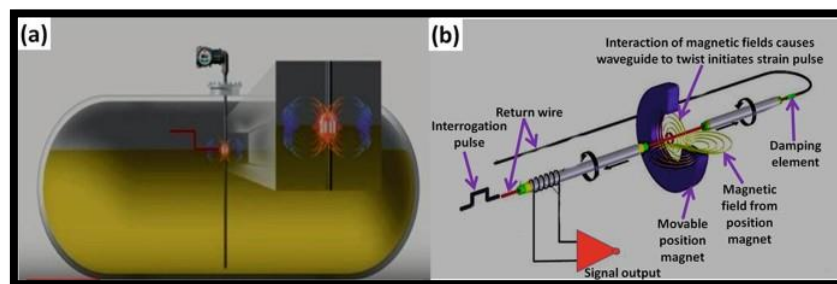


FIGURE II 1 MAGNETO RESTRICTIVE MATERIALS

II.3.4 Electroactive Polymers

There are many forms of electroactive polymers and many are still being refined. They have great potential as the flexibility of how they can be used provide advantages over some of the metals and ceramics mentioned above. Most typically applications include energy harvesting and sensing (see Stretch sense development kit) however some researchers are looking at high voltage, low current actuators.[25]

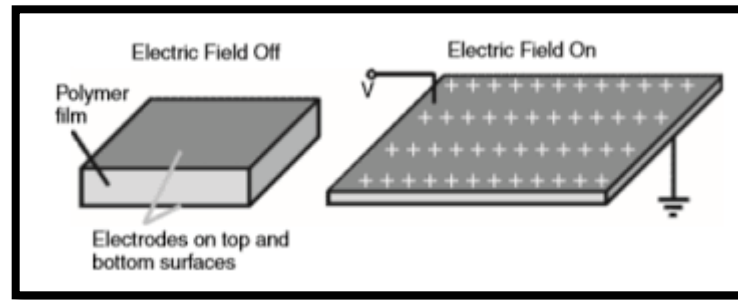


FIGURE II 2 CLASSES OF ELECTROACTIVE POLYMER MATERIAL

II.3.5 Bi-Component Fibers

Adaptive thermal insulation can enable smart clothing that can change its thermal properties based on the environment. Midé has developed bi-component fiber technology where two different materials are co-extruded together to enable shape change depending on ambient temperature.[25]

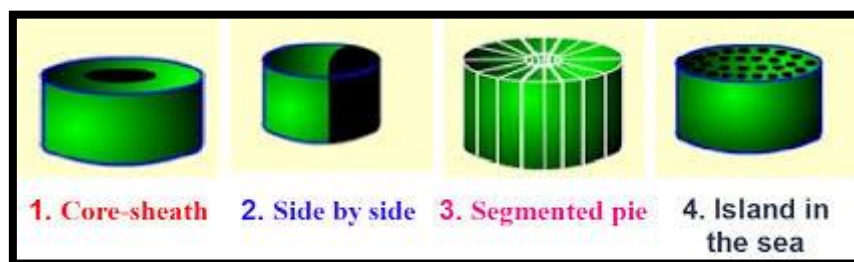


FIGURE II 3 BI-COMPONENT FIBERS

II.4 Application of Smart Materials

Materials Today, smart materials have significant role modern civilization, and they are appeared in most area of technology such as, civil engineering and building, medical, military, robotic machinery, aeronautical technology, industry, nuclear power plant, art, and in some active research groups. In the following sections some applications are discussed.[26]

II.4.2 Piezoelectric Materials

In lighters or portable sparkers with a piezo fuse a sudden and strong pressure is used to produce a voltage. The spark then ignites the gas. A piezo motor is based on the change in mechanical shape of a piezoelectric material when a tension is applied. The material produces ultrasonic or acoustic vibrations and produces a linear or rotary motion. Piezo elements are used in music for acoustic instruments. They are inserted in stringed instruments such as guitar,

violin. The dynamic deformation/vibration of the cords is converted into a small alternating voltage.

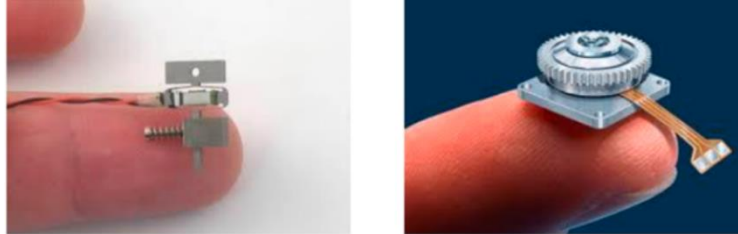


FIGURE II 4 APPLICATION OF PIEZOELECTRIC MATERIALS

II.4.3 Magneto-Rheological Fluids

Magneto-Rheological Fluids have wide application Automotive Industry, Civil Engineering, Household Appliances, Biomedical etc. The MR fluid damper is used in the washing machine to reduce vibrations during spin. The application of semi active control in household applications is still a long way journey; the discussions are only in those areas where the research is primarily about tub dynamics at low spin, about the main drum's resonance frequency. Instead, this work mainly focuses on the vibrations induces due to high rotational velocity.

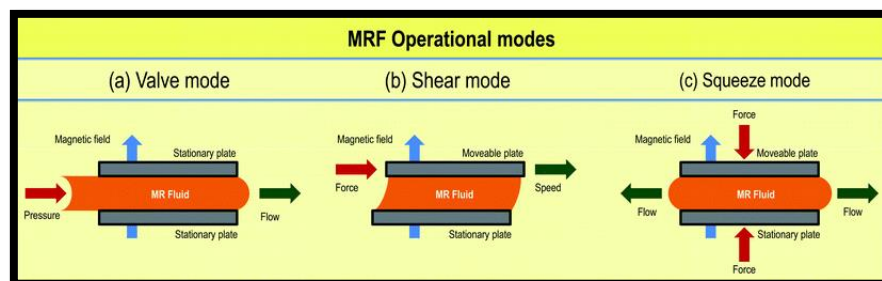


FIGURE II 5 BASIC OPERATIONAL MODES FOR CONTROLLABLE MR FLUID DEVICES

II.4.4 Electro-Rheological Fluids

There are various applications of ERFs in vibration isolators, the automotive industry, shock absorber, clutch. They are also used in building base-isolation and electro-active actuators due to their ability to overcome defects caused by particle aggregation and sedimentation that affects the electro-rheological performance of ERFs building base-isolation and electro-active actuators because they can overcome the defects due to particle aggregation and sedimentation that adepts the electro-rheological performance. Electro-Rheological Fluids

have wide application in Hydraulic Industry, Automobile Industry, Fluid Sealing Industry, Robot Industry.

II.4.6 Telecommunications

- **Enhanced Signal Propagation:** Metamaterials can be used to design antennas with superior performance, such as increased gain, directivity, and bandwidth. This leads to better signal strength and quality.
- **Electromagnetic Interference Reduction:** Metamaterials can be engineered to filter specific frequency bands, reducing electromagnetic interference and improving the clarity of communication signals.
- **Compact and Efficient Antennas:** Metamaterial-based antennas can be smaller in size while maintaining high performance, which is crucial for portable and wearable devices.[27]

II.4.7 Biomedical Applications

- **Medical Imaging:** Metamaterials improve the resolution and efficiency of imaging techniques like MRI and ultrasound by focusing electromagnetic waves more precisely.
- **Therapeutic Devices:** Metamaterials can enhance the effectiveness of devices used for targeted therapies, such as hyperthermia treatment for cancer, by directing energy accurately to affected areas.
- **Biosensors:** Metamaterial-based sensors can detect biomolecules at extremely low concentrations, leading to more sensitive and accurate diagnostic tools.[28]

II.4.8 5G Technology

- **Beam Steering:** Metamaterials can be used to develop advanced beam-steering technologies for 5G networks, enabling efficient and dynamic control of signal direction without moving parts.
- **High-Frequency Operation:** Metamaterials can optimize the performance of components operating at millimeter-wave frequencies, which are essential for 5G communications.

- **Increased Capacity:** By using metamaterials to create more efficient antennas and filters, 5G networks can support a higher number of users and devices simultaneously, improving overall network capacity and speed.[29]

II.5 frequency selective surface

Frequency selective surface (FSS) is a kind of periodic structures that can be used to select incoming electromagnetic waves with different operating frequencies, polarizations and incident angles. Due to this filtering property, FSS can be used in many applications. Conventional FSS usually consists of a 2-D periodic array of slots/apertures etched out of a conducting plate or of conducting patches/strips printed on a dielectric substrate. However, the metallic parts of the conventional FSSs are prone to breakdown, oxidization and corrosion, especially in high-power and high-temperature applications. Therefore, it is imperative to develop new types of FSSs without using metallic structures. Instead of metallic patches, high-permittivity ceramic particles are employed as the elementary unit cell to fabricate all-dielectric metamaterial FSSs.[30]

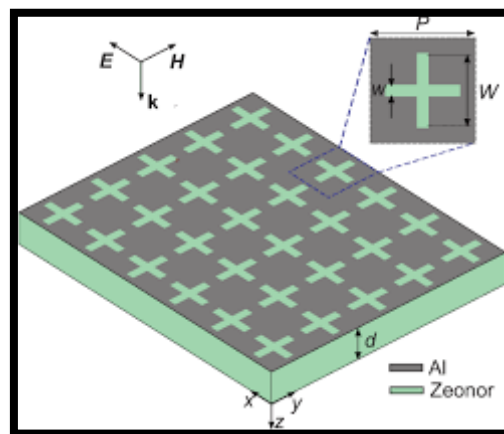


FIGURE II 6 TERAHERTZ FREQUENCY-SELECTIVE SURFACE AND GUIDED-MODE RESONANCE FILTERS

II.6 Types of FSSs

Here, in this section, we categorize the FSSs on the basis of array element, structure design, and application. Figure II.6 gives the taxonomy of the FSS presented in this article.[28]

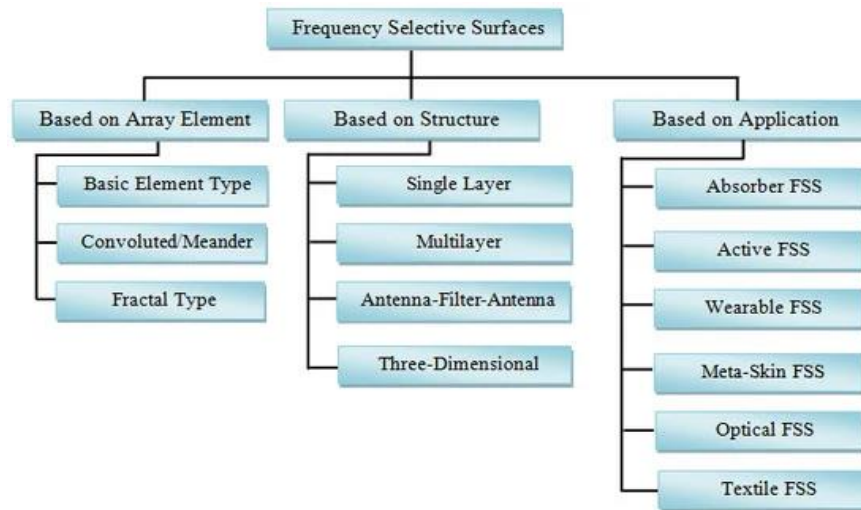


FIGURE II 7 A TAXONOMY OF FSSs

FSSs can be categorized in two primary ways: by their filtering response and by their physical characteristics.

II.6.1 By Filtering Response:

- Low-pass FSS:** This type of FSS allows electromagnetic waves below a certain frequency to pass through, while reflecting those above. An example of a low-pass FSS is the mesh screen door of a microwave oven. The holes in the screen are sized to allow lower frequency radio waves (like Wi-Fi) to pass through, while reflecting the higher frequency microwaves used for cooking.[31]

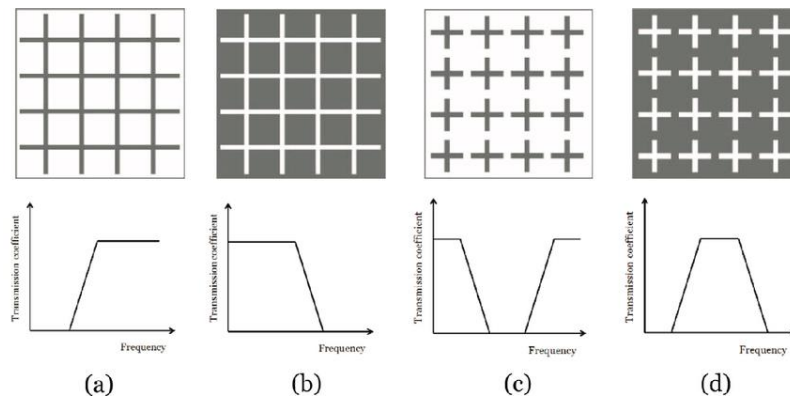


FIGURE II 8 THE FOUR FREQUENCY RESPONSE CHARACTERISTICS OF THE FREQUENCY SELECTIVE SURFACE

- **High-pass FSS:** This type of FSS is the opposite of a low-pass FSS, allowing electromagnetic waves above a certain frequency to pass through, while reflecting those below. High-pass FSSs are less common than low-pass or bandpass FSSs, but they can be used in applications such as filtering out low-frequency noise from a signal.[32]
- **Bandpass FSS:** This type of FSS allows electromagnetic waves within a certain frequency range to pass through, while reflecting those outside of that range. Bandpass FSSs are the most common type, and they are used in a wide variety of applications, such as filtering out unwanted signals in antennas and radar systems.[32]
- **Band-stop FSS:** This type of FSS is the opposite of a bandpass FSS, reflecting electromagnetic waves within a certain frequency range, while allowing those outside of that range to pass through. Band-stop FSSs are used in applications such as reducing electromagnetic interference (EMI) and unwanted radio signals.[32]

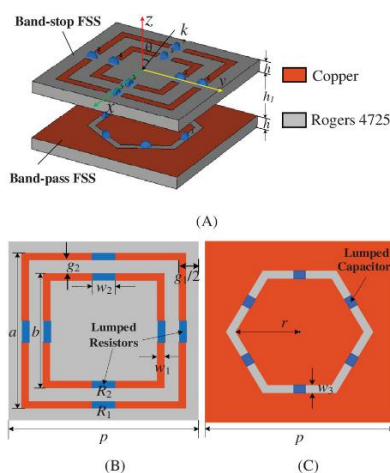


FIGURE II 9 BAND- STOP AND BAND-PASS FSS

II.6.2 By Physical Characteristics:

- **Dipole FSS:** This type of FSS consists of an array of dipole antennas. Dipole FSSs can be designed to have a variety of filtering responses, and they are often used in applications where a high degree of precision is required.
- **Patch FSS:** This type of FSS consists of an array of metallic patches on a dielectric substrate. Patch FSSs are simpler to design and manufacture than dipole FSSs, but they may not offer the same level of performance.[33]

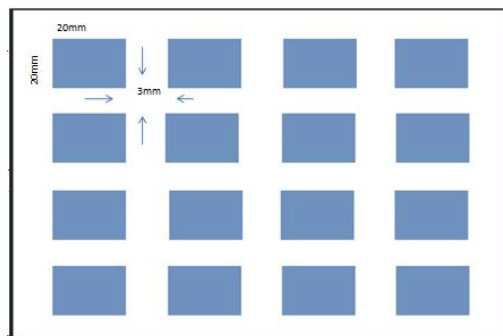


FIGURE II 10 PATCH TYPE FREQUENCY SELECTIVE SURFACE WITHOUT SLOTS

- **Aperture FSS:** This type of FSS is a patterned metallic sheet that is placed in front of an antenna. Aperture FSSs are often used to improve the directivity of an antenna or to reduce unwanted radiation.[34]
- **Metallochromic FSS:** This type of FSS is made of a combination of metal and ceramic materials. Metallochromic FSSs can be designed to have a wider range of filtering responses than traditional FSSs.[34]

II.7 Future Challenges and Potential Applications of FSSs

FSSs have been used in many applications, including reflectors, antenna radomes, radar absorbing materials, polarizers, and composite metamaterials. Although this research area is relatively old but enormously dynamic and fast growing, it bears a broad pedigree in applications as well as theory since numerous matured design and analysis tools have been developed. However, noteworthy problems related to theoretical and practical importance still to be solved, for example, the development of doubly curved FSS, non-periodic FSS.

Generally speaking, required performance characteristics of an FSS are broader bandwidth, faster roll-off (sharp band edges), and stability with the variation of incident angles and polarizations of an incoming EM wave. It has been well identified from the earlier literature

and in this review paper that the array element nature, its geometry, inter-element spacing, dielectric, and structure profiles are the defining structure parameters of an FSS. Several critical challenges are to be addressed in successful designing of FSS structures. Choice of an appropriate FSS element, unit cell dimensions, substrate profile, and layer/iterations are of the major importance. Controlling these parameters to fit in demanding and compact applications has been a challenging task and it generally requires critical and good EM behavior analysis of an FSS. We perceive a number of challenging areas in significant exploration and practical applications of FSS where they might sharply impact the future trends include:[31]

1. Miniaturized Design

Miniaturized FSS are required in some applications, especially in antenna radoms, because of flexibility requirement. In addition, large inter-element spacing and element dimensions may not be suitable in realizing curved surfaces. Reduced unit cell size is enviable with fairly small electrical dimensions and higher angular stability of the FSSs. Therefore, the concept of the miniaturized array element has been evolved broadly, since they separate the operating bands from the grating lobes. Recently, various FSS miniaturization techniques have been utilized by different element shapes, Still, this challenge needs to be solved for many low-space and rigid applications.

2. Higher operating bandwidth

A key challenge in FSSs design and theory is its limited operating BW, especially it is important to improve the BW for single layer FSS structures, Although multilayer FSS and many schemes are presented in this regard, however, FBW is still not satisfactory. Meandered/convoluted/Interwoven, loop and fractal elements have been used to minimize the unit cell dimensions along with the thickness of the FSS, but these may not necessarily improve the BW. Even though multilayer build helps to achieve an optimal design, but attaining higher BW, especially at lower operating frequency is the foremost challenge for the FSS designers.

3. Transmission through energy saving Glass

Passband FSSs are designed to allow for the transmission of useful wireless communication signals through energy saving window glass in modern buildings with the key requirements of stable frequency response, and reasonably higher BW. However, FSS apertures need to be narrow as much possible for higher thermal insulation and offer a big challenge. Coating of FSS is to be etched carefully to reduce the degradation of thermal insulation and to maintain the aesthetic feature of the window glass. The possibility of getting a strong resonating

FSS and perfect transmission response is a challenge due to oxide that is present in the coated layer; however, recently improved performances are reported by careful designing.

4. FSS for smart cities applications

Nowadays, wireless mobile communication takes place mostly in the 6 GHz and below frequency bands. A significant issue occurs in the Wi-Fi band with the dense working environment, such as conference venues and Condo buildings. Besides, smart city applications require access at millimeter wave frequencies higher than 24 GHz. Practical challenges for such higher band are poor EM wave propagation through the objects and structure materials. The FSS placed on and inside buildings are specifically designed to improve the reception and transmission of radio frequency signals. Still, smart cities applications require managing these propagation and interference issues to properly perform at these low and higher bands of frequencies.

5. Problem of Transmission losses

FSS structures have been designed to exhibit lossless transmission response, such as in Radom design; nonetheless, they show high transmission losses in real scenarios. Although fundamental theoretical analysis suggests these to be only a fraction, in measurement these losses are quite high on a low-loss substrate. Many sources may account for such losses e.g., Ohmic-losses, dielectric heating losses, radiation losses, and separating all of them is not easy.

II.8 Conclusion

The technology of smart materials by its nature, is a highly interdisciplinary field. Starting from the field of basic sciences such as physics, chemistry, mechanics, computing and electronics it also covers the applied sciences and engineering such as aeronautics and mechanical engineering. This may explain the slow progress of the application of smart structures in engineering systems, even if the science of smart materials is moving very fast. In the present scenario, the most promising technologies for lifetime efficiency and improved reliability include the use of smart materials and structures. Understanding and controlling the composition and microstructure of any new materials are the ultimate objectives of research in this field and is crucial to the production of good smart materials.

Two important features of a frequency selective surface (FSS) are bandwidth and frequency stability. Methods of increasing FSS bandwidth include, among others, decreasing

inter-element spacing and increasing the thickness of the supporting dielectric layer. The shape of the FSS element also determines its bandwidth. To achieve any desired bandwidth, a combination of these methods is often required. The present work focuses on designing an FSS element where shape alone is the most important feature in determining its bandwidth. The elements are a combination of two known FSS elements with close resonant frequencies but not located in the same frequency band. The FSS's are designed to act as reflectors. The second part of this paper discusses frequency stabilization techniques, focusing on rectangular arrays of tripoles and cross dipoles. These elements have poor frequency stability with angle of incidence for parallel polarization. Dielectric loading and skewed arrays help minimize the problem. In the present work, a new method based on varying the element's impedance by partially removing the conducting patch at the center of the element is introduced.

Chapter III

Metamaterial based Smart materials

III. Metamaterials based smart Materials

III.1 Introduction

We can categorize a material as either a conductor or a dielectric based on its constitutive parameters, such as dielectric permittivity, magnetic permeability, and refractive index, which define its electromagnetic behavior. In the case of artificial materials or metamaterials, it is now possible to manipulate these parameters through precise control over their structure, including dimensions, geometry, orientation, and layout, to achieve specific electromagnetic properties.

In this work, we focus on designing smart materials by utilizing metamaterials super cells with two different behaviors.

III.2 Metamaterial super cell

The super cell is a square matrix composed of a specific number of metamaterial unit cells; in this part we designed super cells (4X4) to study the effect of super cell number on the metamaterial electromagnetic response.

In this project we went with a super cell that is composed of 16 elements arranged in the form of the square matrix 4X4 like the previous supercell, we made it entirely of type A metamaterial. Then we will observe its feedback while changing the state of one or more of its components, after that we will also observe the opposite case of each of the primary cases like explained in figures **Figure III.1**, **Figure III.2** and **Figure III.3**.

Two different behaviors are obtained depending on the state of the switches (ON or OFF).

III.2.1 Connected-cross type metamaterial super cell (type A)

The ON state of switches constitutes a connected-cross type metamaterial super cell, as depicted in figure III.2, which is referred to as (type A) during this dissertation. This metamaterial super cell follows the Drude frequency-dependent model for real part of effective dielectric permittivity. It presents a two value at the plasma frequency $f_p = 52 \text{ GHz}$. The real part of the effective permeability pass from 0.7 values as figure III.2 shows. the refraction index presents a real part close to zero.

- The imaginary part in all cases represents the loss of the magnetic and electric field.

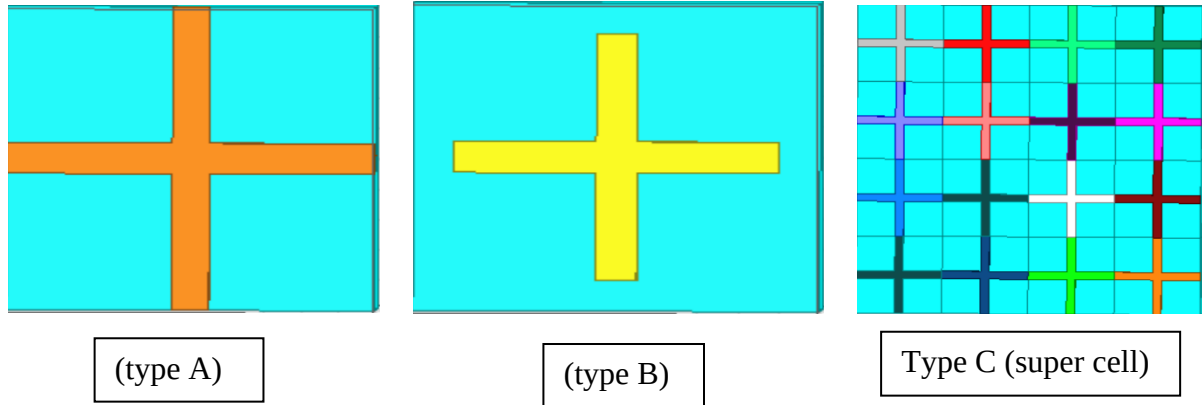


FIGURE III 1 TYPE, (B); DISCONNECTED TYPE, TYPE C (SUPER CELL) FULL VIEW

- Type (C) represent the super cell (4X4) of our project we put different colors just to show that we can control each unit alone.

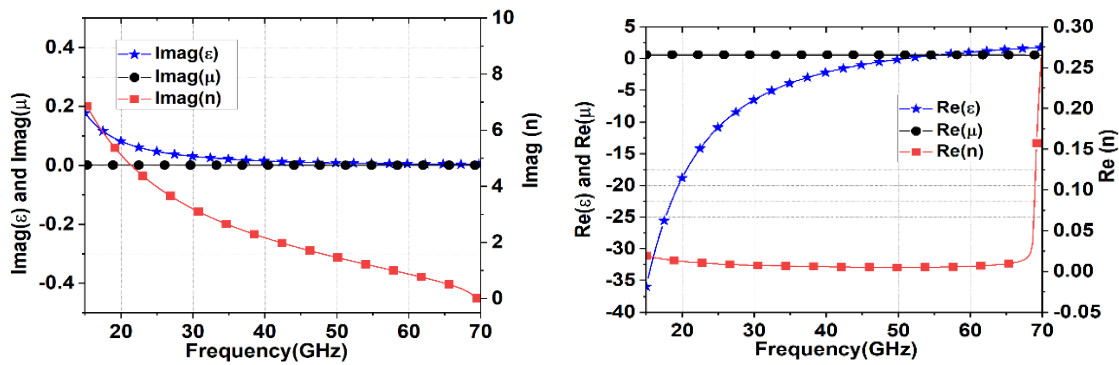
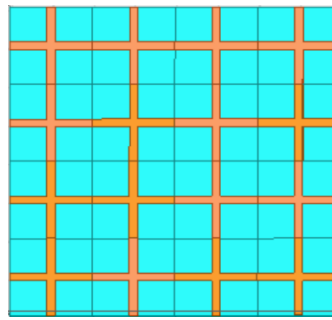


FIGURE III 2 REPRESENT THE CASE 1 (TYPE A) ALL CELLS CONNECTED

III.2.2 Metamaterial unit cell type disconnected-cross (type B)

The OFF state of switches constitutes a metamaterial unit cell type disconnected-cross, as depicted in figure III.3 which referred to as (type B) during this dissertation. Dielectric permittivity of this type of metamaterial follows the Lorentz resonant frequency-dependent model. It exhibits a constant value of 2.75 in the real part of effective dielectric permittivity over all the frequency range and begins to decrease at $f=50$ GHz until it is zero, the real part of

the effective permeability is close to 1. The real part of the refractive index is about 1.67 at $f=50$ GHz and also presents an increase transition at 70 GHz, as shown in figure III.3

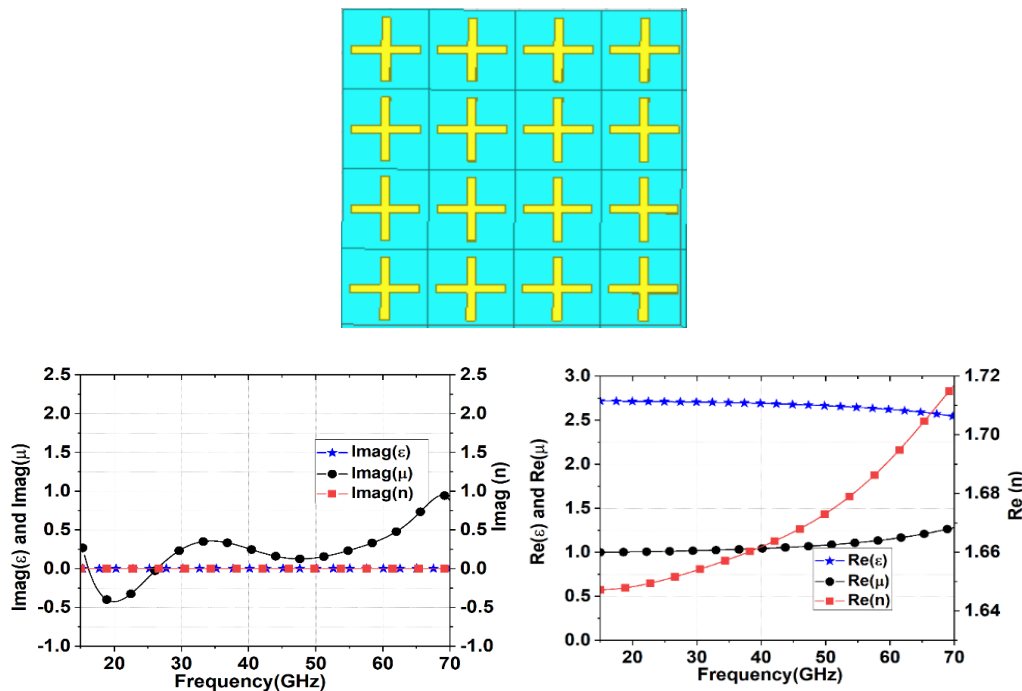


FIGURE III 3 REPRESENT THE CASE 1' (TYPE B) ALL CELLS DICONNECTED

III.3 all the cases with their opposite

- we are going to study the cases and their opposite with percentage calculation for the cases with connected cells.

III.3.1 Cases with 6,25 % connected cells

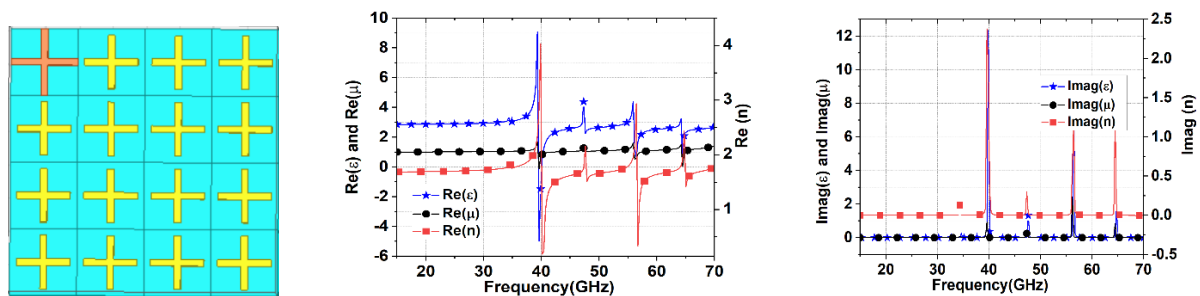


FIGURE III 4 CASE 3' (TYPE B) WITH ONE CONNECTED CELL

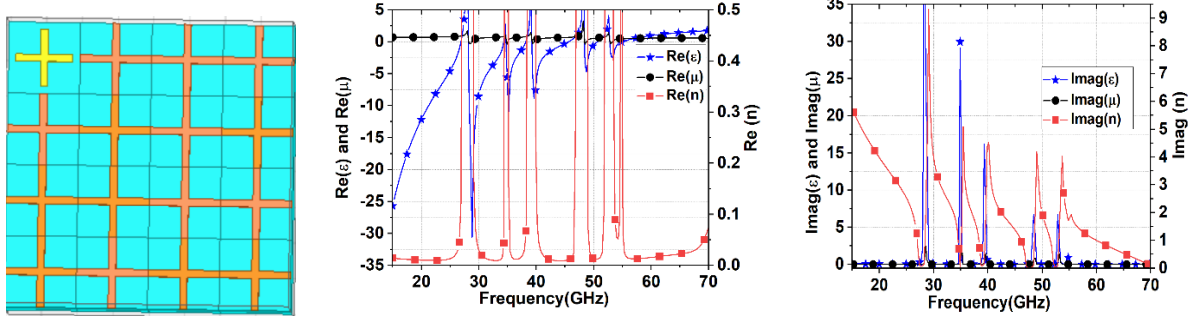


FIGURE III 5 CASE 3 (TYPE A) WITH ONE DISCONNECTED CELL

- In this case we have 6.25% (**Figure III.4**) connected cells the comportment is conductor, compared to case 3 93.75% the comportment is dielectric.
- In the **Figure III.4** in the real part of effective dielectric permittivity and the effective permeability and the refraction index, and to be more precise we can tell from the figures above that from $f=15$ GHz to $f=38$ GHz the comportment is dielectric and from $f=40$ GHz to $f=70$ GHz the Lorentz resonant frequency-dependent model.
- In the **Figure III.5** in the real part, in the case 3 from $f=15$ GHz to $f=27$ GHz the comportment of permittivity is Drude frequency-dependent model and the permeability, refraction index is dielectric and from $f=25$ GHz to 57 GHz is Lorentz resonant frequency-dependent model in the three variables.

III.3.2 Cases with 12,5 % connected cells

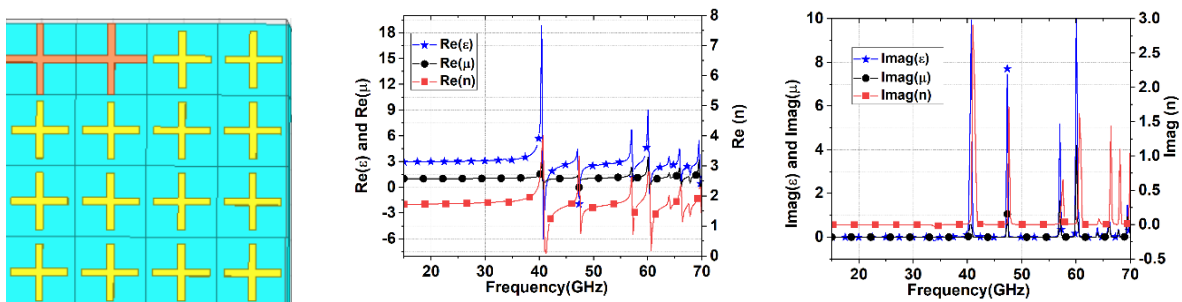


FIGURE III 6 CASE 4' (TYPE B) WITH TWO CONNECTED CELLS

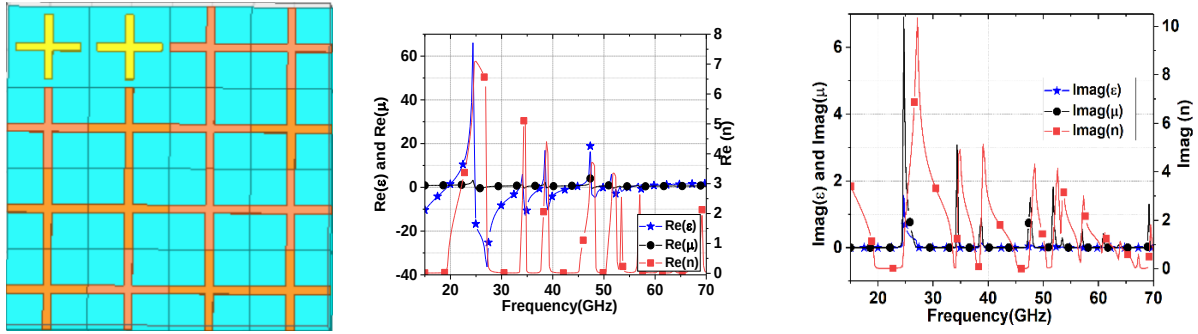


FIGURE III 7 CASE 4 (TYPE A) WITH 2 DISCONNECTED CELLS

- In **Figure III.7** we disconnected 1 cell compared **Figure III.5** which lead to comportment change in the real part, the comportment of the case 4' in **Figure III.6** is the same with the case 3' in **Figure III.4**.
- In the case 4 **Figure III.7** we see from $f=15\text{GHz}$ to $f=20\text{GHz}$ is Drude frequency-dependent model for the permittivity and from $f=40\text{GHz}$ to $f=65\text{GHz}$ is Lorentz resonant frequency-dependent model and from $f=65\text{GHz}$ to $f=70\text{GHz}$ dielectric for the three variables.

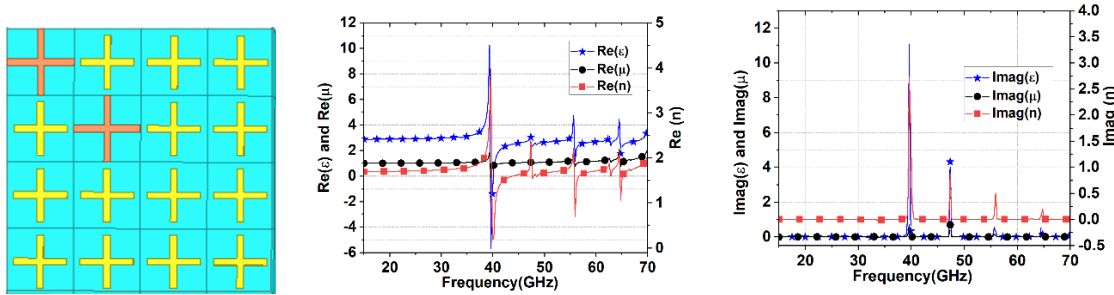


FIGURE III 8 CASE 9' (TYPE B) WITH TWO CONNECTED CELLS

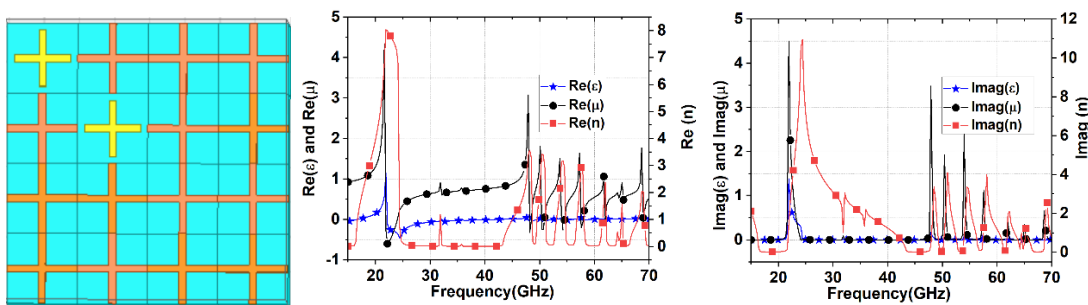


FIGURE III 9 CASE 9 (TYPE A) WITH TWO DISCONNECTED CELLS

- In this case **Figure III.8** we see that are have the same comportment with the case 3' in **Figure III.4**

- in the case in **Figure III.9** we can tell from the figure above that from $f=15\text{GHz}$ to $f=18\text{GHz}$ is Lorentz resonant frequency-dependent model in effective dielectric permittivity, the effective permeability and the refraction index from $f=20\text{GHz}$ to $f=55\text{GHz}$ is dielectric and from $f=55\text{GHz}$ to $f=70\text{GHz}$ the comportment is Lorentz resonant frequency-dependent model.

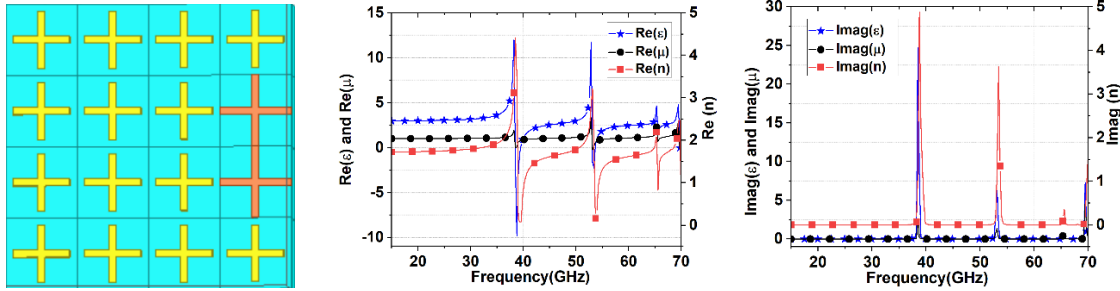


FIGURE III 10 CASE 17 (TYPE B) WITH TWO CONNECTED CELLS

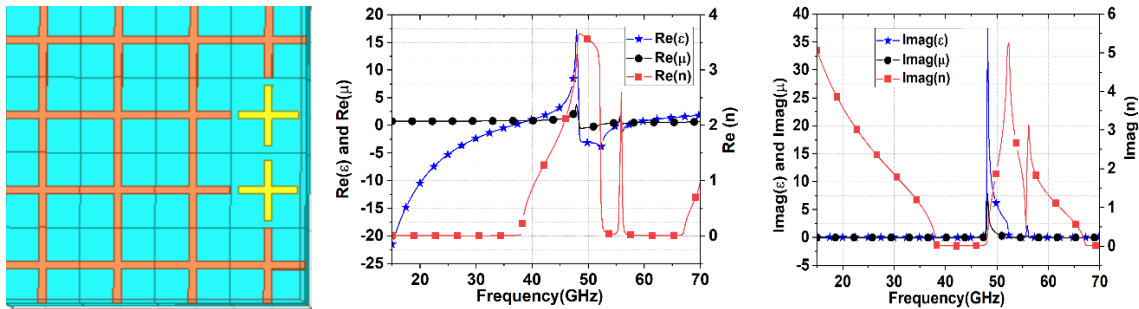


FIGURE III 11 CASE 17' (TYPE B) WITH 16 CONNECTED CELLS

- In the case of **Figure III.10** the comportment is the same with the case 3' in **Figure III.4** and the case 4' in **Figure III.6**.
- In the case of **Figure III.11** we observe that from $f=15\text{GHz}$ to $f=40\text{GHz}$ is dielectric for the permeability and the refraction index as for the permittivity is drude frequency-dependent model .and from $f=40\text{GHz}$ to $f=60\text{GHz}$ the comportment is Lorentz resonant frequency-dependent model and from $f=60\text{GHz}$ to $f=70\text{GHz}$ is dielectric for the three variables.

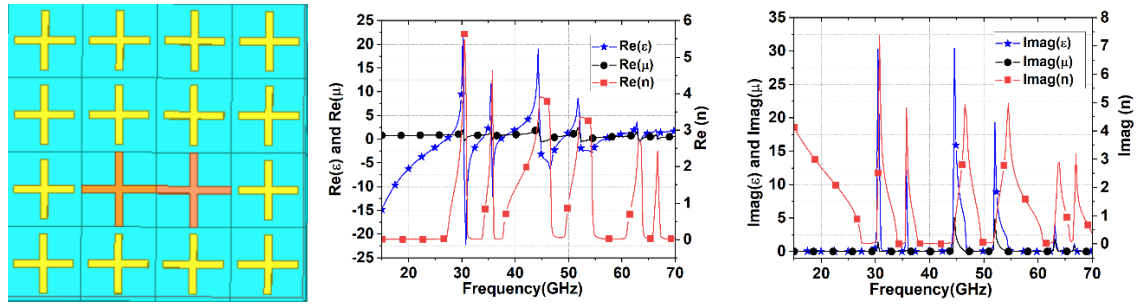


FIGURE III 12 CASE 20' (TYPE B) WITH 14 CONNECTED CELLS

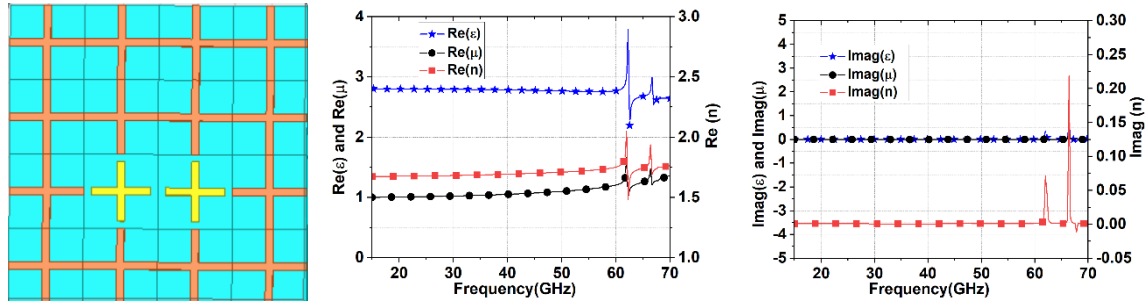


FIGURE III 13 CASE 20 (TYPE B) WITH 14 CONNECTED CELLS

- In **Figure III.12** from $f=15\text{GHz}$ to $f=30\text{GHz}$ is Drude frequency-dependent model for the permittivity, and the permeability, the refraction index is dielectric. And from $f=30\text{GHz}$ to $f=70\text{GHz}$ is Lorentz resonant frequency-dependent model for the three variables. While **Figure III.13** from $f=15\text{GHz}$ to $f=60\text{GHz}$ is dielectric and from $f=60\text{GHz}$ to $f=70\text{GHz}$ is Lorentz resonant frequency-dependent model for the three variables.
- We observe that in **Figure III.6**, **Figure III.8**, **Figure III.10**, and **Figure III.12** all have 12.5% connected cells, the comportment is conductor.
- The other cases **Figure III.8**, **Figure III.9**, **Figure III.11**, **Figure III.13** all have 87.5% of their comportment dielectric.

III.3.3 Cases who have 25 % connected cells

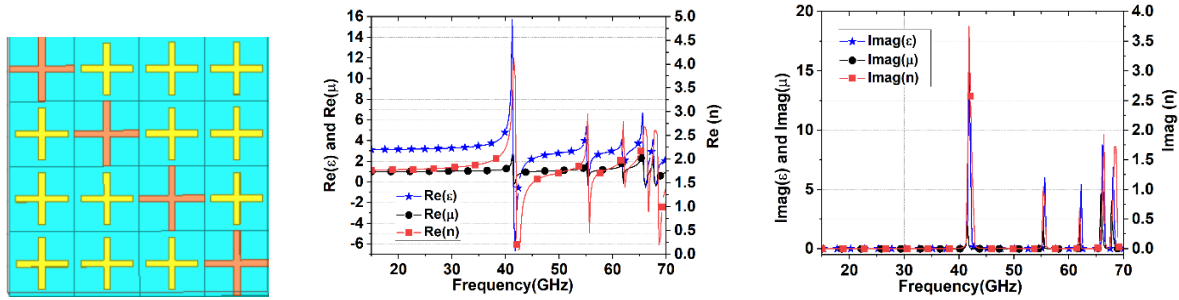


FIGURE III 14 CASE 6' (TYPE B) WITH FOUR CONNECTED CELLS

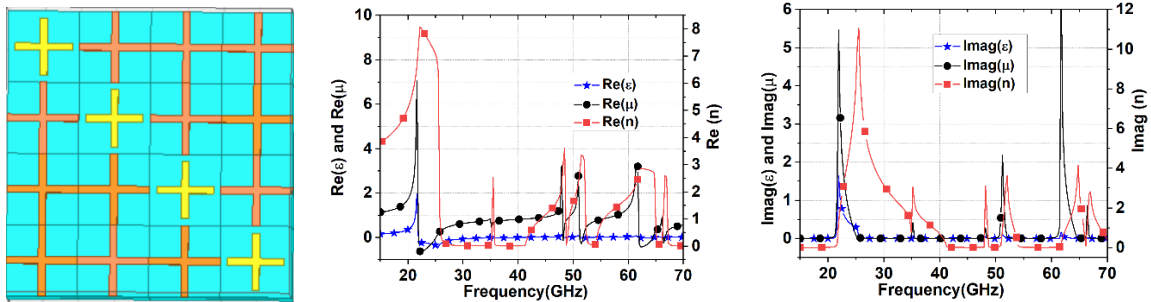


FIGURE III 15 CASE 6 (TYPE A) WITH 4 DISCONNECTED CELLS

- In the case of **Figure III.14** we see that are have the same comportment with the case 3' in **Figure III.4** and the case 9'in the **Figure III.8**.
- In the case 6 in the **Figure III.15** is sharing the same comportment with the case 9 in **Figure III.9**.

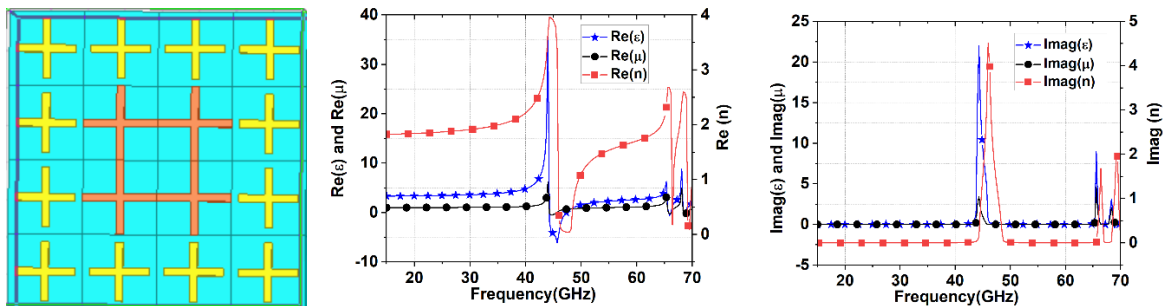


FIGURE III 16 CASE 21 (TYPE A) WITH DISCONNECTED CELLS

- In the **Figure III.16** we see that from $f=15\text{GHz}$ to $f=40\text{GHz}$ is dielectric to permittivity and permeability, refraction index. And from $f=40\text{GHz}$ to $f=70\text{GHz}$ is Lorentz resonant frequency-dependent model.

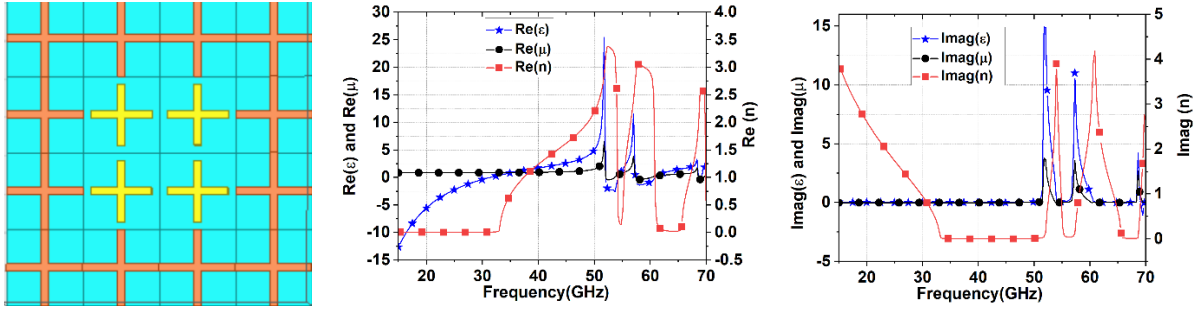


FIGURE III 17 CASE 21' (TYPE B) WITH 12 CONNECTED CELLS

- In the **Figure III.17** as we used 4 type B cells, both cases shared the same comportment from $f=15\text{GHz}$ to $f=40\text{GHz}$ the permeability and refraction index is dielectric .and permittivity is drude frequency-dependent model and from $f=40\text{GHz}$ to $f=70\text{GHz}$ is lorentz resonant frequency-dependent model.

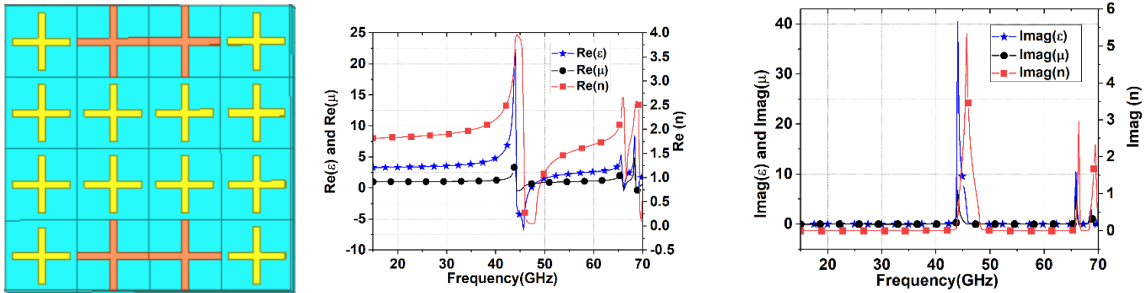


FIGURE III 18 CASE 16 (TYPE A) WITH 12 DISCONNECTED CELLS

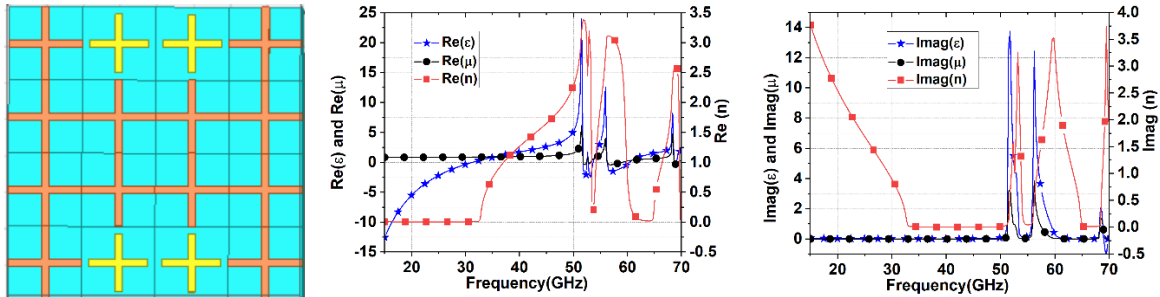


FIGURE III 19 CASE 16' (TYPE B) WITH 12 CONNECTED CELLS

- From **Figure III.16** and **Figure III.18** we see that we get the same comportment
- Also **Figure III.19** and **Figure III.17** share the same comportment.

III.3.4 Cases who have 37,5 % connected cells

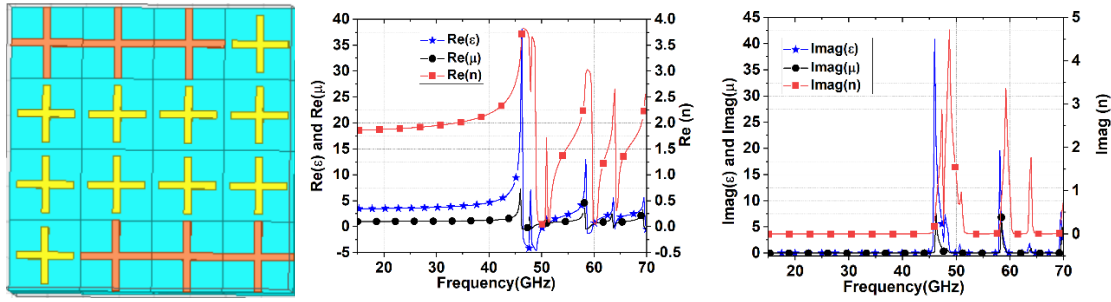


FIGURE III 20 CASE 19' (TYPE B) WITH 6 CONNECTED CELLS

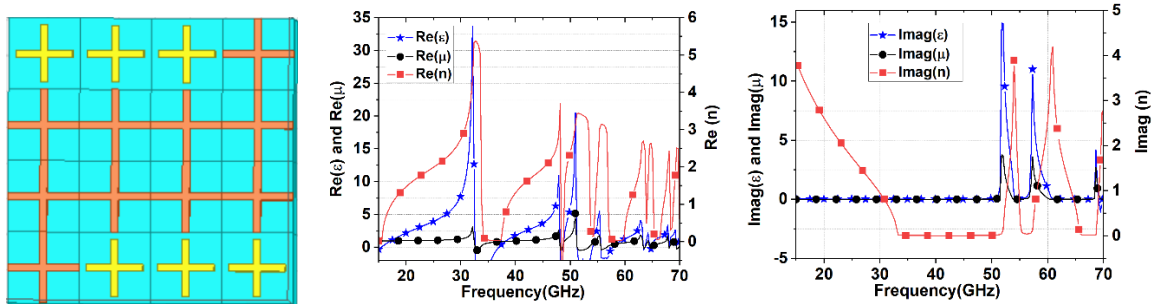


FIGURE III 21 CASE 19 (TYPE A) WITH 6 DISCONNECTED CELLS

Figure III.21 and **Figure III.20** are opposite cases with 6 connected cells and 6 disconnected cells for the both cases we can tell from the figures above that:

- In the **Figure III.21** from $f=15\text{GHz}$ to $f=70\text{GHz}$ is the comportment is Lorentz resonant frequency-dependent model for the three variables.
- In the **Figure III.20** from $f=15\text{GHz}$ to $f=40\text{GHz}$ is dielectric for the three variables .and from $f=40\text{GHz}$ to $f=70\text{GHz}$ the comportment is Lorentz resonant frequency-dependent model.

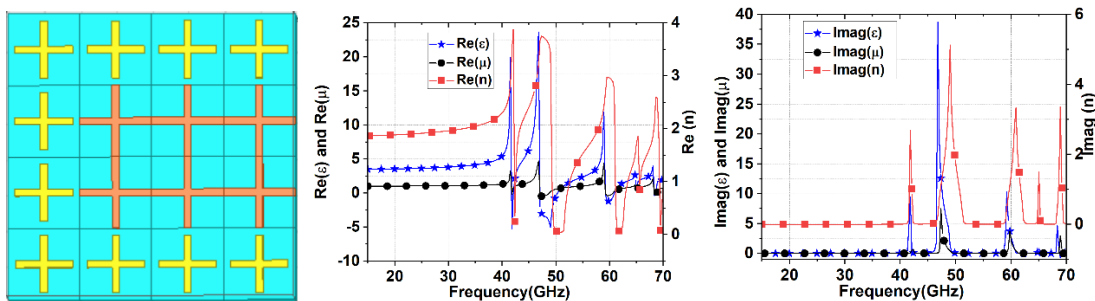


FIGURE III 22 CASE14 (TYPE A) WITH 10 DISCONNECTED CELLS

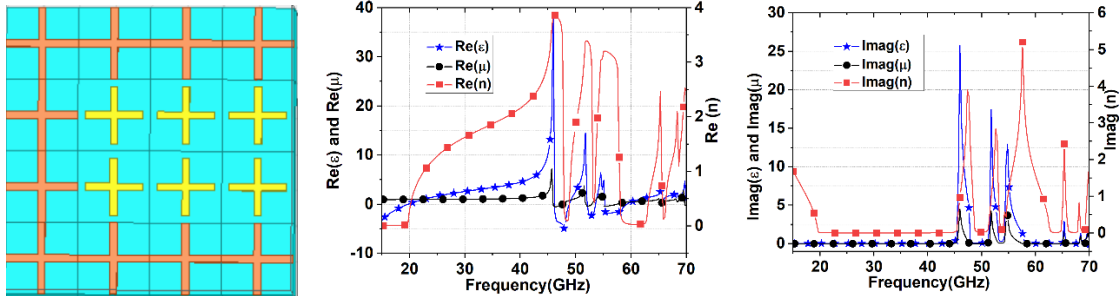


FIGURE III 23 CASE 14' (TYPE B) WITH 10 CONNECTED CELLS

Figure III.22 and **Figure III.23** are opposite cases with 6 connected cells and 6 disconnected cells for the both cases we can tell from the figures above that:

- In the **Figure III.22** from $f=15\text{GHz}$ to $f=40\text{GHz}$ is dielectric for the three variables .and from $f=40\text{GHz}$ to $f=70\text{GHz}$ the comportment is Lorentz resonant frequency-dependent model.
- In the **Figure III.23** from $f=15\text{GHz}$ to $f=40\text{GHz}$ is Drude frequency-dependent model for the permittivity and the permeability is dielectric as for refraction index >1 .and from $f=40\text{GHz}$ to $f=70\text{GHz}$ the comportment is Lorentz resonant frequency-dependent model for the three variables.

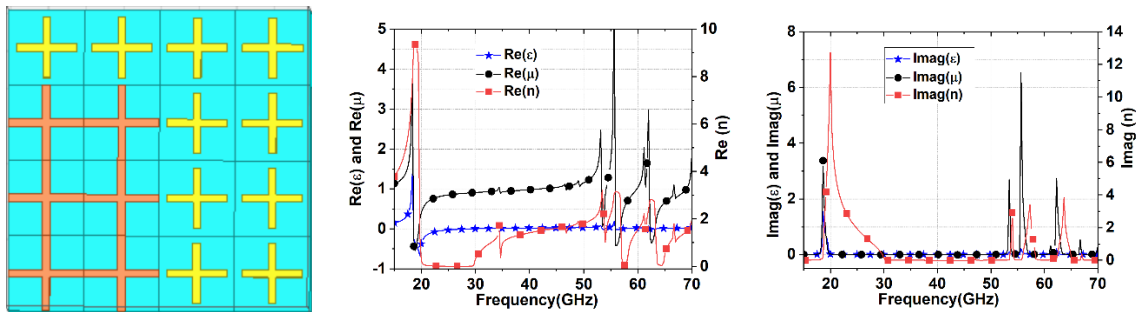


FIGURE III 24 CASE 10 (TYPE A) WITH 10 DISCONNECTED CELLS

- In these cases, we see that are have the same comportment, in the real part we notice The figures 24,9,15 confirms that these cases share the same comportment in the real part

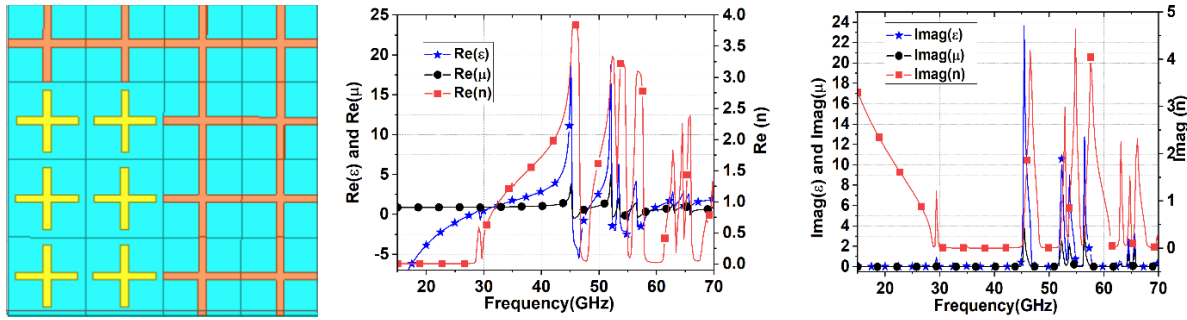


FIGURE III 25 CASE 10' (TYPE B) WITH 10 CONNECTED CELLS

- In **Figure III.25** the comportment from $f=15\text{GHz}$ to $f=30\text{ GHz}$ the permeability and the refraction index is dielectric and the permittivity is drud frequency-dependent model. From $f=30\text{GHz}$ to $f=70\text{GHz}$ the three variables is Lorentz resonant frequency-dependent model.

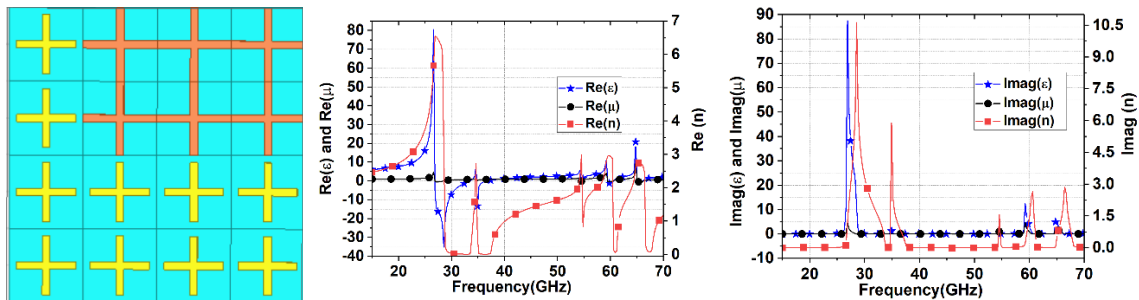


FIGURE III 26 CASE 8' (TYPE B) WITH 6 CONNECTED CELLS

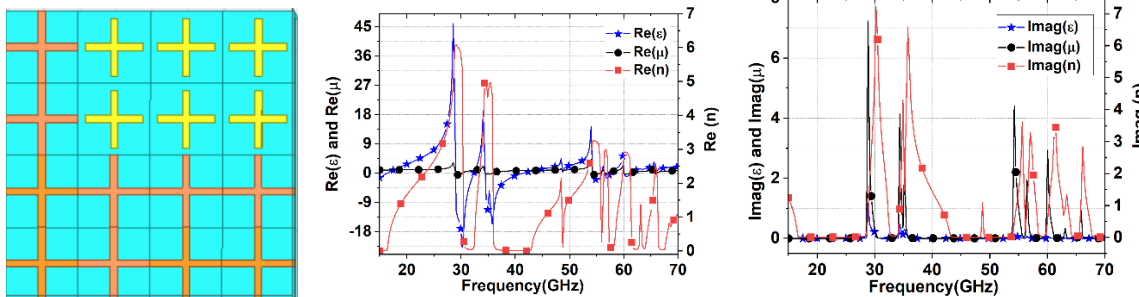


FIGURE III 27 CASE 8 (TYPE A) WITH 6 DISCONNECTED CELLS

- In **Figure III.26**, case 8' from $f=15\text{GHz}$ to $f=27\text{ GHz}$ Lorentz resonant frequency-dependent model and from $f=27\text{GHz}$ to $f=55\text{GHz}$ permittivity and the permeability id dielectric as for the refraction index >1 . From $f=55\text{GHz}$ to $f=70\text{GHz}$ the comportment is Lorentz resonant frequency-dependent model for the three variables.
- In the **Figure III.27** of case 8 from $f=15\text{GHz}$ to $f=70\text{ GHz}$ Lorentz resonant frequency-dependent model in the three variables

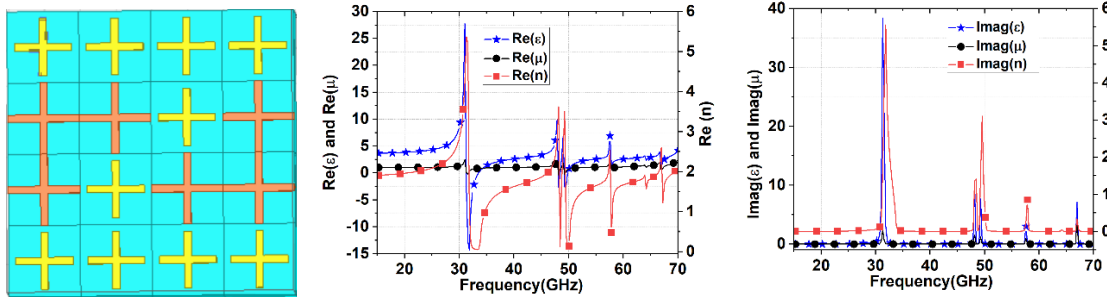


FIGURE III 28 CASE 13 (TYPE A) WITH 10 DISCONNECTED CELLS

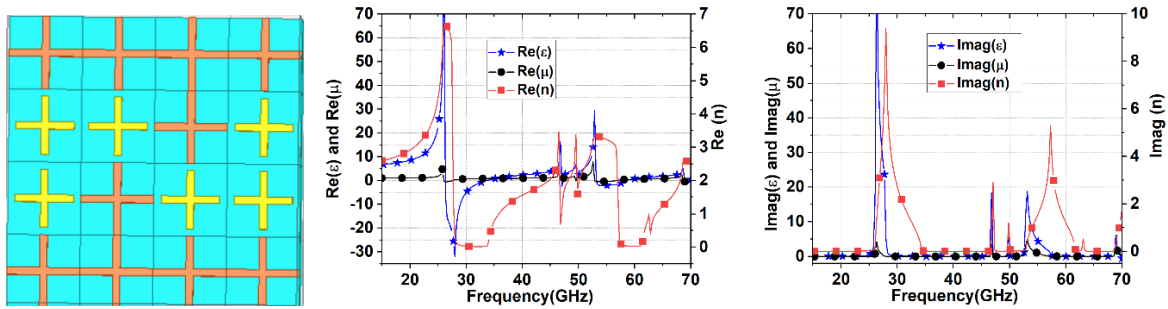


FIGURE III 29 CASE 13' (TYPE B) WITH 10 CONNECTED CELLS

- **Figure III.28** and **Figure III.29** are opposite cases with 10 connected cells and 10 disconnected, we can see that the results from both are almost identical and we can tell from the figure above that from $f=15\text{GHz}$ to $f=70\text{GHz}$ the permeability is dielectric and permittivity, refraction index is Lorentz resonant frequency-dependent model.

III.3.4 Cases who have 43,75 % connected cells

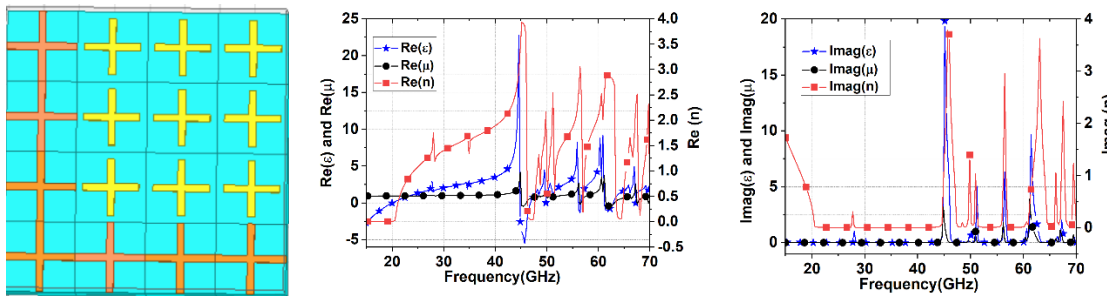


FIGURE III 30 CASE 5 (TYPE B) WITH 9 DISCONNECTED CELLS

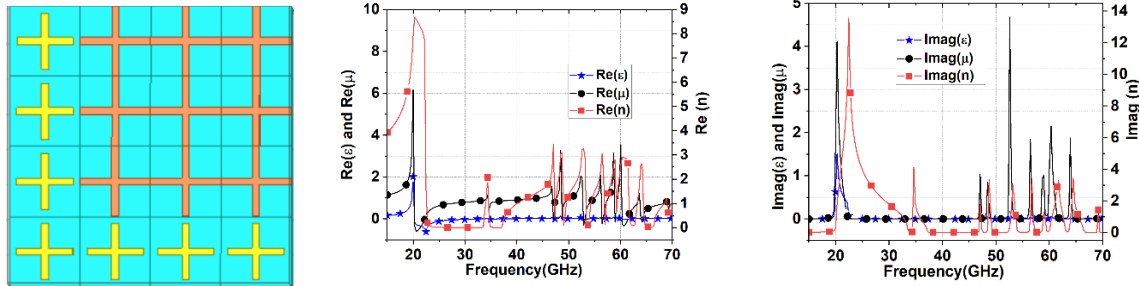


FIGURE III 31 CASE 5' (TYPE B) WITH 9 CONNECTED CELLS

- In the **Figure III.30** in case 5 we see that from $f=15\text{GHz}$ to $f=40\text{GHz}$ the permeability is dielectric and the refraction index $n>1$ and the permittivity is drud frequency-dependent model. And from $f=40\text{GHz}$ to $f=70\text{GHz}$ the comportment is Lorentz resonant frequency-dependent model in the three variables.
- In the **Figure III.31** Case 5' the comportment is the same with the cases in the figures 24,9,15,31

➤ Next, we are going to study cases with 8 connected cells and 8 disconnected cells (50% type A cells, 50% type B cells).

III.3.6 Cases who have 50 % connected cells

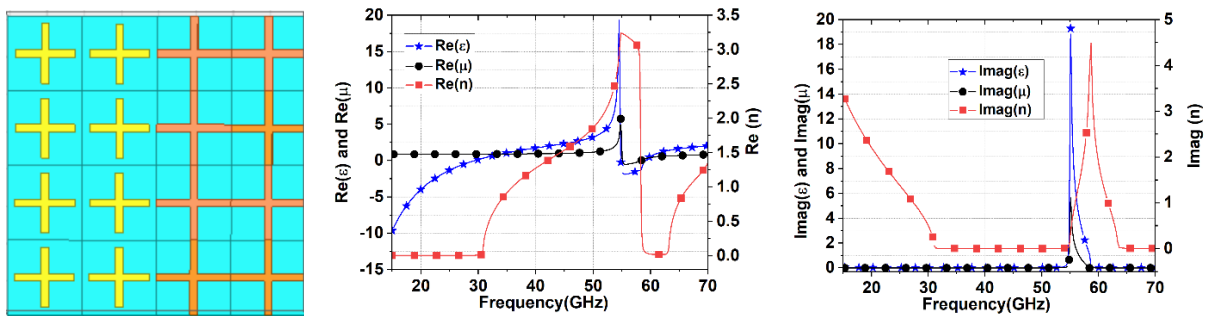


FIGURE III 32 CASE 7 (TYPE A) WITH 8 DISCONNECTED CELLS

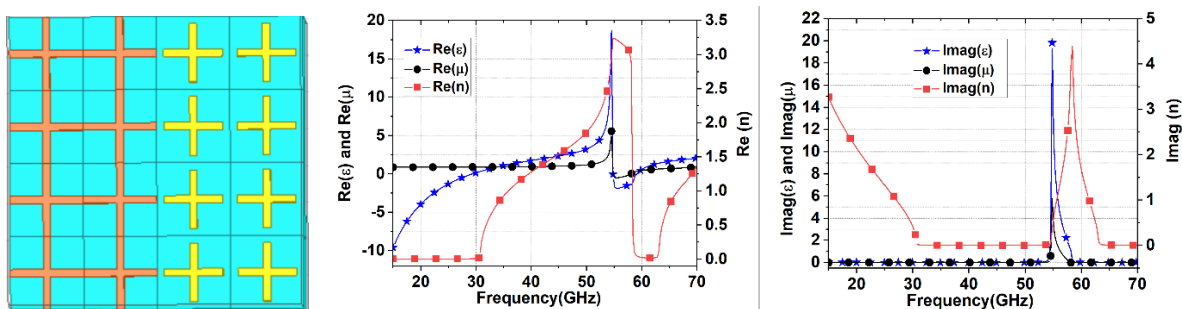


FIGURE III 33 CASE 7' (TYPE B) WITH 8 CONNECTED CELLSC

- **Figure III.32** and **Figure III.33** are opposite cases with 8 connected cells and 8 disconnected, we can observe that the output from these two cases is exactly the same, which is from $f=15\text{GHz}$ to $f=50\text{GHz}$ in the effective permeability is dielectric as for the permittivity is Drude frequency-dependent model. And from $f=50\text{GHz}$ to $f=70\text{GHz}$ Lorentz resonant frequency-dependent model and refraction index from $f=15\text{GHz}$ to $f=31\text{GHz}$ the comportment is dielectric and from $f=31\text{GHz}$ to $f=50\text{GHz} > 1$.

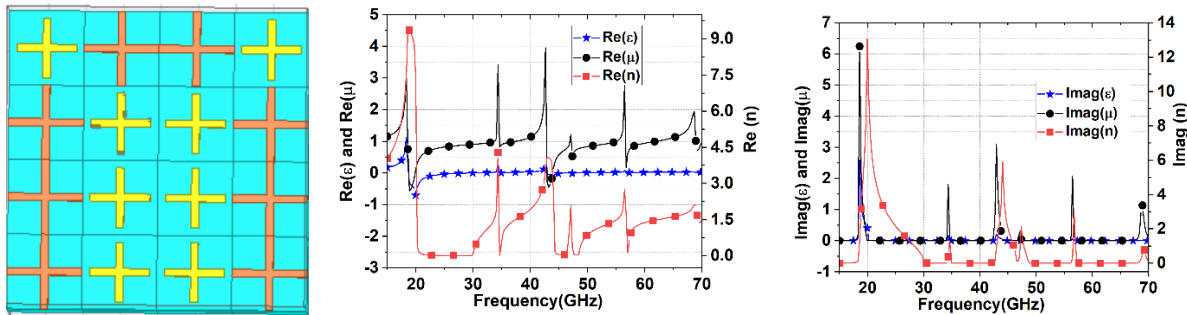


FIGURE III 34 CASE 15 (TYPE A) WITH 8 DISCONNECTED CELLS

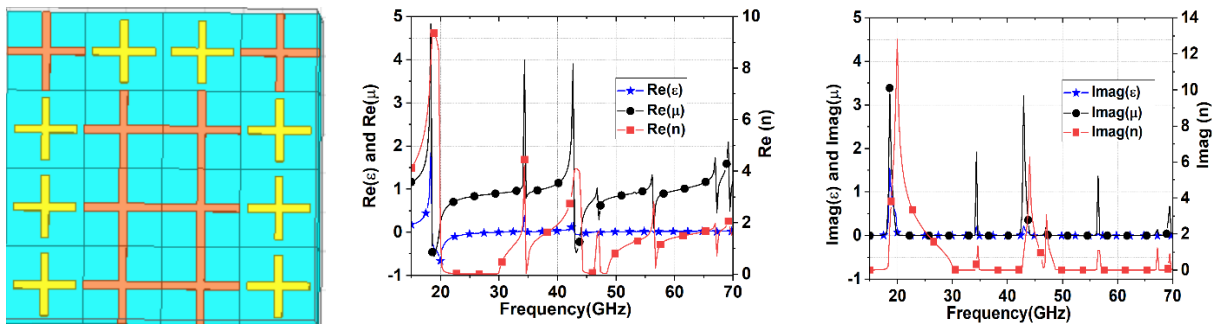


FIGURE III 35 CASE 15' (TYPE B) WITH 8 CONNECTED CELLS

In **Figure III.34** and **Figure III.35** we tried another combination of 8 type A cells and 8 type B cells and as we can see the results were different from the previous one from **Figure III.23** **Figure III.24**.

- In these two cases, we see that they have the same comportment, in the real part we notice. The figures 25,26 confirm that these cases share the same comportment, we can tell from the figure above that from $f=15\text{GHz}$ to $f=20\text{GHz}$ is Lorentz resonant frequency-dependent model in effective dielectric permittivity, the effective permeability and the refraction index and from $f=20\text{GHz}$ to $f=70\text{GHz}$ the permittivity dielectric and the permeability and the refraction index is Lorentz resonant frequency-dependent.

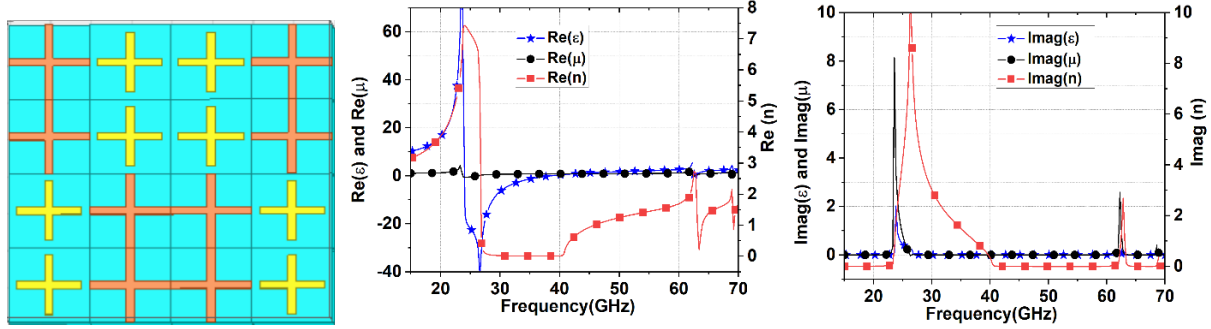


FIGURE III 36 CASE 12 (TYPE A) WITH 8 DISCONNECTED CELLS

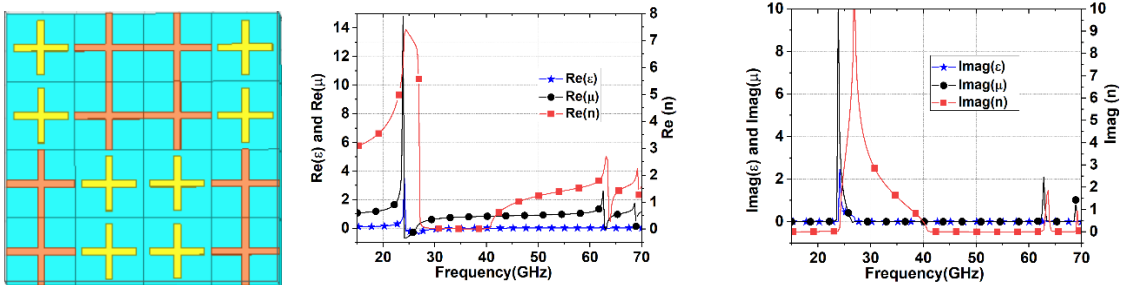


FIGURE III 37 CASE 12' (TYPE B) WITH 8 CONNECTED CELLS

Figure III.36, Figure III.37 outputs further prove our previous deduction from Figure III.32

Figure III.33, Figure III.34 Figure III.35., we can now conclude that opposite cells with 8 connected cells and 8 disconnected cells will always give the same comportment.

III.3.7 Cases who have 75% connected cells

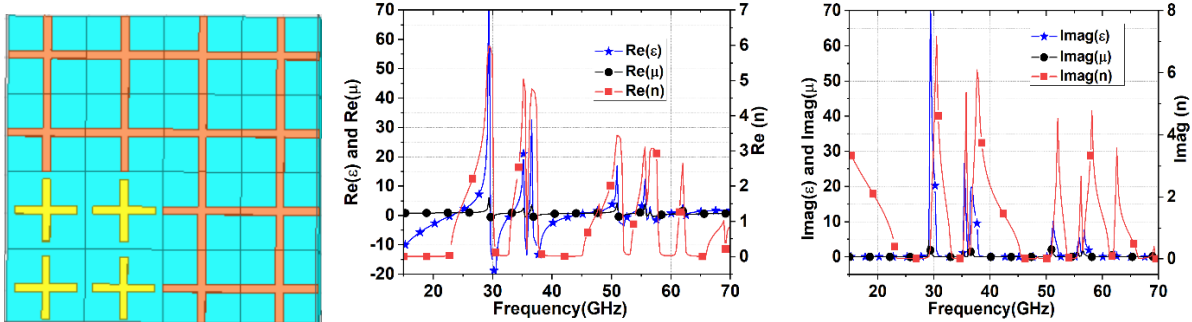


FIGURE III 38 CASE 11' (TYPE B) WITH 12 CONNECTED CELLS

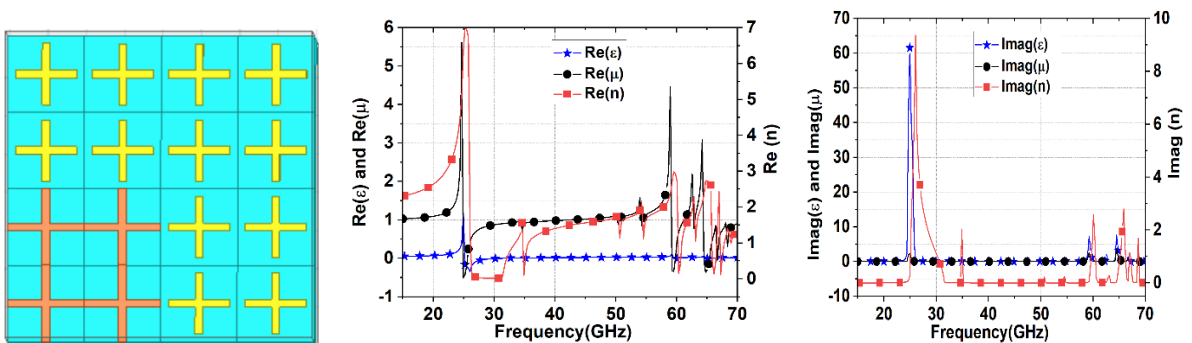
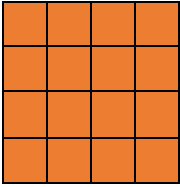
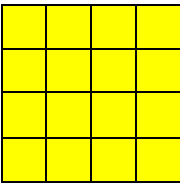
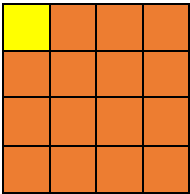
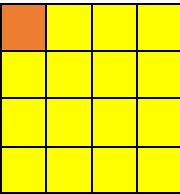
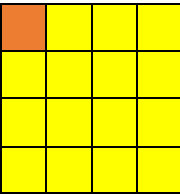


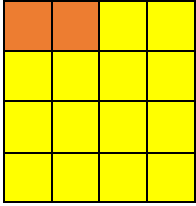
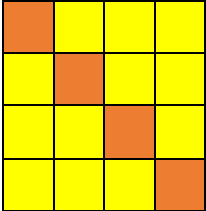
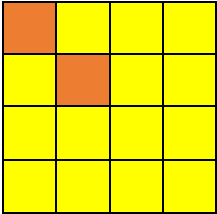
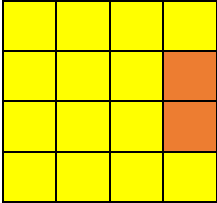
FIGURE III 39 CASE 11 (TYPE A) WITH 12 DISCONNECTED CELLS

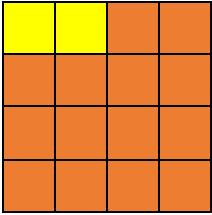
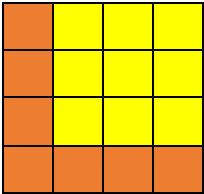
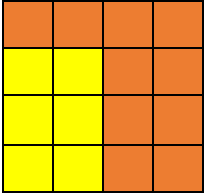
Figure III.39 and **Figure III.38** are opposite cases with 12 connected cells and 12 disconnected, we can see that the results from both are not identical and we can tell from the figures above that:

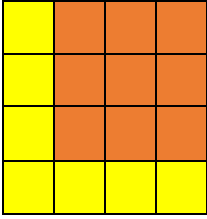
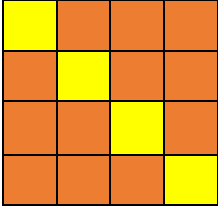
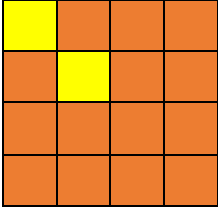
- In **Figure III.39** we observe from $f=15\text{GHz}$ to $f=30\text{ GHz}$ is Lorentz resonant frequency-dependent model and from $f=30\text{GHz}$ to $f=55\text{ GHz}$ the permittivity and permeability is dielectric and the refraction index is Lorentz resonant frequency-dependent model. And from $f=55\text{GHz}$ to $f=70\text{GHz}$ the permeability and the refraction index is Lorentz and the permittivity is dielectric.
- In the **Figure III.38** from $f=15\text{GHz}$ to $f=25\text{ GHz}$ is Drude frequency-dependent model for the permittivity. And dielectric for the permeability and refraction index. and from $f=25\text{GHz}$ to $f=70\text{ GHz}$ the permittivity and permeability and the refraction index is Lorentz resonant frequency-dependent model.

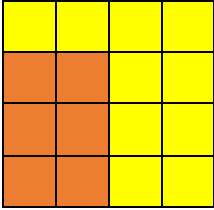
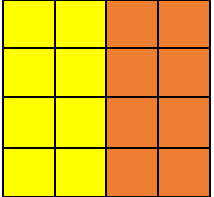
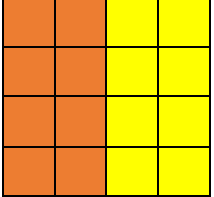
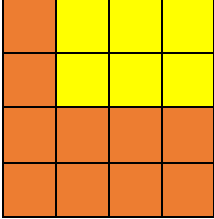
TABLE 1 TABLE REPRESENT ALL THE CASES AND THEIR OPPOSITE

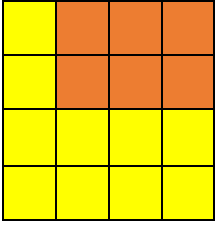
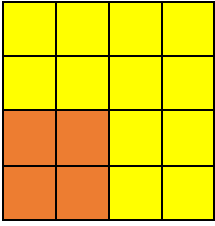
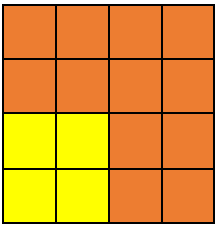
Cases	Range	n	ϵ_{eff}	μ_{eff}
 Case 1	[15 – 70]	$n \approx 0$	$\epsilon_{eff} < 2$ $f_p=52$	$\mu_{eff} < 1$
 Case 1'	[15 – 50]	$n > 1$	$\epsilon_{eff} = 2.75$	$\mu_{eff} = 1$
	[50 – 70]	$n > 1$	$\epsilon_{eff} < 2.75$	$\mu_{eff} > 1$
 Case 3	[15 – 25]	$n \approx 0$	$\epsilon_{eff} < 0$ $f_p=26$	$\mu_{eff} = 1$
	[25 – 57]	$f_0=27$ $f_1=36$ $f_2=39$ $f_3=48$ $f_4=56$	$f_0=27$ $f_1=36$ $f_2=39$ $f_3=48$ $f_4=54$	$f_0=27$ $f_1=36$ $f_2=39$ $f_3=48$ $f_4=54$
 Case 3'	[57 – 70]	$n \approx 0$	$\epsilon_{eff} > 0$ $f_p=57$	$\mu_{eff} = 1$
	[15 – 38]	$n > 1$	$\epsilon_{eff} = 3$	$\mu_{eff} = 1$
 Case 3'	[38 – 70]	$f_0=40$ $f_1=48$ $f_2=57$ $f_3=65$	$f_0=40$ $f_1=48$ $f_2=57$ $f_3=65$	$f_0=40$ $f_1=57$ $f_2=65$

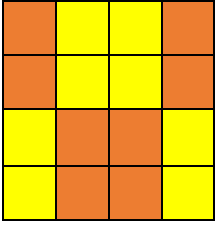
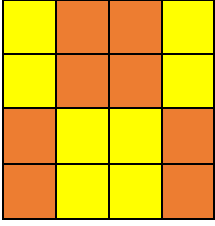
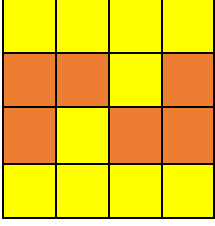
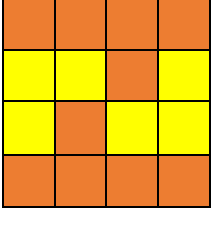
 Case 4'	[15 – 38]	$n > 1$	$\epsilon_{eff} = 3$	$\mu_{eff} = 1$
	[38 – 70]	$f_0=40$ $f_1=48$ $f_2=58$ $f_3=60$ $f_4=64$ $f_5=66$ $f_6=68$	$f_0=40$ $f_1=48$ $f_2=58$ $f_3=60$ $f_4=64$ $f_5=66$ $f_6=68$	$f_0=40$ $f_1=48$ $f_2=58$ $f_3=60$ $f_4=64$ $f_5=66$ $f_6=68$
 Case 6'	[15 – 38]	$n > 1$	$\epsilon_{eff} = 3$	$\mu_{eff} = 1$
	[38 – 70]	$f_0=41$ $f_1=55$ $f_2=62$ $f_3=66$ $f_4=68$	$f_0=41$ $f_1=55$ $f_2=62$ $f_3=66$ $f_4=68$	$f_0=41$ $f_1=55$ $f_2=62$ $f_3=66$ $f_4=68$
 Case 9'	[15 – 38]	$n > 1$	$\epsilon_{eff} = 3$	$\mu_{eff} = 1$
	[38 – 70]	$f_0=40$ $f_1=56$ $f_2=66$	$f_0=40$ $f_1=56$ $f_2=66$	$f_0=40$ $f_1=56$ $f_2=66$
 Case 17	[15 – 35]	$n > 1$	$\epsilon_{eff} = 3$	$\mu_{eff} = 1$
	[35 – 70]	$f_0=38$ $f_1=54$ $f_2=65$	$f_0=38$ $f_1=54$ $f_2=65$	$f_0=38$ $f_1=54$ $f_2=65$

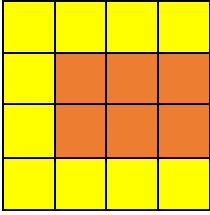
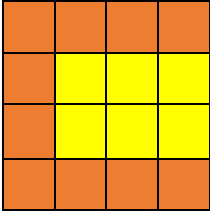
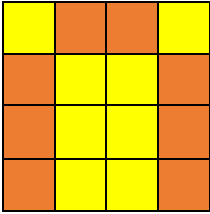
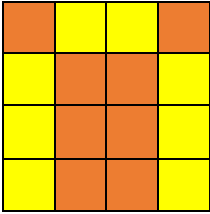
 Case 4	[15 – 23]	$n > 1$	$\epsilon_{eff} > 0$	$\mu_{eff} = 0$
	[23 – 56]	$f_0=25$ $f_1=35$ $f_2=39$ $f_3=48$ $f_4=52$ $f_5=57$	$f_0=25$ $f_1=35$ $f_2=38$ $f_3=48$ $f_4=52$	$f_0=25$ $f_1=35$ $f_2=47$
	[56 – 70]	$n \approx 0$	$\epsilon_{eff} = 0$	$\mu_{eff} = 0$
 Case 5	[15 – 40]	$n > 1$	$\epsilon_{eff} > 0$ $f_p=20$	$\mu_{eff} = 1$
	[40 – 70]	$f_0=45$ $f_1=50$ $f_2=52$ $f_3=56$ $f_4=62$ $f_5=67$	$f_0=45$ $f_1=49$ $f_2=56$ $f_3=60$ $f_4=67$	$f_0=45$ $f_1=56$ $f_2=61$
	[15 – 40]	$n > 1$	$\epsilon_{eff} > 0$	$\mu_{eff} = 1$
	[40 – 70]	$f_0=45$ $f_1=52$ $f_2=54$ $f_3=56$ $f_4=62$ $f_5=64$ $f_6=66$	$f_0=45$ $f_1=52$ $f_2=54$ $f_3=56$ $f_4=62$ $f_p=28$	$f_0=45$ $f_1=52$ $f_2=54$ $f_3=56$ $f_4=62$
 Case 10'				

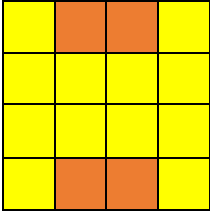
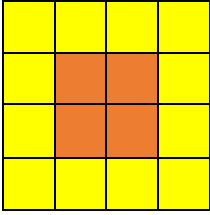
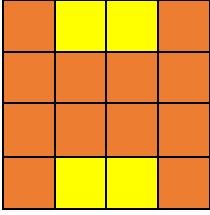
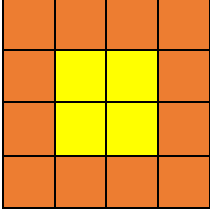
 Case 5'	[15 – 25]	$f_0=20$	$f_0=20$	$f_0=20$
	[25 – 70]	$f_0=34$ $f_1=47$ $f_2=48$ $f_3=53$ $f_4=57$ $f_5=58$ $f_6=60$ $f_7=63$	$\varepsilon_{eff} = 0$	$f_0=34$ $f_1=47$ $f_2=48$ $f_3=53$ $f_4=57$ $f_5=58$ $f_6=60$ $f_7=63$
	[15 – 28]	$f_0=22$	$f_0=22$	$f_0=22$
 Case 6	[28 – 70]	$f_0=35$ $f_1=48$ $f_2=52$ $f_3=61$ $f_4=66$	$\varepsilon_{eff} = 0$	$f_0=48$ $f_1=51$ $f_2=61$ $f_3=66$
	[15 – 30]	$f_0=21$	$f_0=21$	$f_0=21$
 Case 9	[30 – 70]	$f_0=32$ $f_1=48$ $f_2=50$ $f_3=53$ $f_4=57$ $f_5=61$ $f_6=65$ $f_7=69$	$\varepsilon_{eff} = 0$	$f_0=32$ $f_1=48$ $f_2=50$ $f_3=53$ $f_4=57$ $f_5=61$ $f_6=65$ $f_7=69$

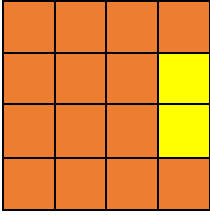
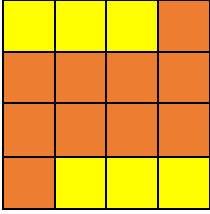
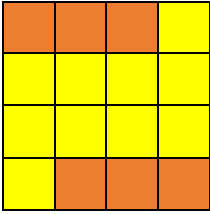
 Case 10	[15 – 20]	$f_0=18$	$f_0=18$	$f_0=18$
	[20 – 70]	$f_0=35$ $f_1=49$ $f_2=53$ $f_3=55$ $f_4=62$ $f_5=66$	$\varepsilon_{eff} = 0$	$f_0=35$ $f_1=49$ $f_2=53$ $f_3=55$ $f_4=62$ $f_5=66$
 Case 7  Case 7'	[15 – 30]	$n \approx 0$		
	[30– 50]	$n > 1$		
	[15 – 50]		$\varepsilon_{eff} > 0$ $f_p=30$	$\mu_{eff} = 1$
	[50 – 70]	$f_0=55$	$f_0=55$	$f_0=55$
 Case 8	[15 – 70]	$f_0=29$ $f_1=35$ $f_2=49$ $f_3=55$ $f_4=57$ $f_5=60$ $f_6=66$	$f_0=29$ $f_1=35$ $f_2=49$ $f_3=55$ $f_4=60$	$f_0=29$ $f_1=35$ $f_2=55$ $f_3=60$

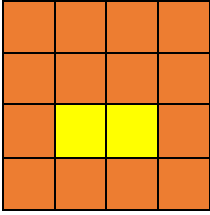
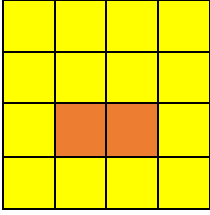
 Case 8'	[15 – 27]	$f_0=26$	$f_0=26$	$f_0=26$
	[27 – 55]	$n > 1$	$\varepsilon_{eff} = 0$	$\mu_{eff} = 0$
	[55 – 70]	$f_0=55$ $f_1=60$ $f_2=65$	$f_0=59$ $f_1=65$	$f_0=59$ $f_1=65$
 Case 11	[15 – 30]	$f_0=25$	$f_0=25$	$f_0=25$
	[30 – 55]	$f_0=35$ $f_1=50$ $f_2=55$	$\varepsilon_{eff} = 0$	$\mu_{eff} = 1$
	[55 – 70]	$f_0=59$ $f_1=62$ $f_2=64$	$\varepsilon_{eff} = 0$	$f_0=59$ $f_1=62$ $f_2=64$
 Case 11'	[15 – 25]	$n \approx 0$	$\varepsilon_{eff} > 0$ $f_p=23$	$\mu_{eff} = 0$
	[25 – 70]	$f_0=30$ $f_1=35$ $f_2=37$ $f_3=51$ $f_4=55$ $f_5=57$ $f_6=62$	$f_0=30$ $f_1=35$ $f_2=50$ $f_3=55$ $f_4=62$	$f_0=30$ $f_1=35$ $f_2=50$ $f_3=55$ $f_4=62$

 Case 12	[15 – 35]	$f_0=25$	$f_0=25$	$f_0=25$
	[35 – 70]	$f_0=62$ $f_1=69$	$\varepsilon_{eff} = 0$	$\mu_{eff} = 0$
 Case 12'	[15 – 30]	$f_0=24$	$f_0=24$	$f_0=24$
	[30 – 60]	$n > 1$	$\varepsilon_{eff} = 0$	$\mu_{eff} = 1$
	[60 – 70]	$f_0=62$ $f_1=69$	$\varepsilon_{eff} = 0$	$f_0=62$ $f_1=69$
 Case 13	[15 – 70]	$f_0=31$ $f_1=58$ $f_2=59$ $f_3=64$ $f_4=68$	$f_0=31$ $f_1=48$ $f_2=58$ $f_3=66$	$\mu_{eff} = 1$
	[15 – 70]	$f_0=27$ $f_1=48$ $f_2=50$ $f_3=52$	$f_0=27$ $f_1=48$ $f_2=50$ $f_3=52$	$f_0=27$ $f_1=48$ $f_2=50$ $f_3=52$
 Case 13'				

 Case 14	[15 – 40]	$n = 2$	$\varepsilon_{eff} = 3$	$\mu_{eff} = 1$
	[40 – 70]	$f_0=41$ $f_1=47$ $f_2=59$ $f_3=65$ $f_4=69$	$f_0=41$ $f_1=47$ $f_2=59$ $f_3=65$ $f_4=69$	$f_0=41$ $f_1=47$ $f_2=59$ $f_3=65$ $f_4=69$
 Case 14'	[15 – 40]	$n > 1$	$\varepsilon_{eff} > 0$ $f_p=20$	$\mu_{eff} = 1$
	[40 – 70]	$f_0=46$ $f_1=52$ $f_2=55$ $f_3=65$ $f_4=69$	$f_0=46$ $f_1=52$ $f_2=55$ $f_3=65$	$f_0=46$ $f_1=52$ $f_2=55$ $f_3=65$
 Case 15	[15 – 70]	$f_0=18$	$f_0=18$	$f_0=18$
		$f_1=35$ $f_2=42$ $f_3=47$ $f_4=57$ $f_5=67$	$\varepsilon_{eff} = 0$	$f_1=35$ $f_2=42$ $f_3=47$ $f_4=57$ $f_5=67$
 Case 15'				

 Case 16  Case 18	[15 – 40]	$n > 1$	$\varepsilon_{eff} = 3$	$\mu_{eff} = 1$
	[40 – 70]	$f_0=45$ $f_1=65$ $f_2=69$	$f_0=45$ $f_1=65$ $f_2=69$	$f_0=45$ $f_1=65$ $f_2=69$
 Case 16'  Case 18'	[15 – 40]	$n > 1$	$\varepsilon_{eff} < 0$ $f_p=30$	$\mu_{eff} = 1$
	[40 – 70]	$f_0=51$ $f_1=55$ $f_2=69$	$f_0=51$ $f_1=55$ $f_2=69$	$f_0=51$ $f_1=55$ $f_2=69$

 Case 17'	[15 – 40]	$n \approx 0$	$\varepsilon_{eff} < 0$ $f_p=38$	$\mu_{eff} = 1$
	[40 – 60]	$f_0=48$ $f_1=55$	$f_0=48$ $f_1=55$	$f_0=48$ $f_1=55$
	[60 – 70]	$n \approx 0$	$\varepsilon_{eff} = 2$	$\mu_{eff} = 0$
 Case 19	[15 – 70]	$f_0=32$ $f_1=49$ $f_2=51$ $f_3=55$ $f_4=63$ $f_5=64$ $f_6=68$	$f_0=32$ $f_1=49$ $f_2=51$ $f_3=55$ $f_4=63$ $f_5=64$ $f_6=68$	$f_0=32$ $f_1=49$ $f_2=51$ $f_3=55$ $f_4=63$ $f_5=64$ $f_6=68$
 Case 19'	[15 – 40]	$n > 1$	$\varepsilon_{eff} = 3$	$\mu_{eff} = 1$
	[40 – 70]	$f_0=47$ $f_1=48$ $f_2=59$ $f_3=63$	$f_0=47$ $f_1=48$ $f_2=59$ $f_3=63$	$f_0=47$ $f_1=48$ $f_2=59$ $f_3=63$

 Case 20	[15 – 60]	$n > 1$	$\varepsilon_{eff} = 2.75$	$\mu_{eff} = 1$
	[60 – 70]	$f_0=62$ $f_1=67$	$f_0=62$ $f_1=67$	$f_0=62$ $f_1=67$
 Case 20'	[15 – 30]	$n \approx 0$	$\varepsilon_{eff} < 0$ $f_p=28$	$\mu_{eff} = 1$
	[30 – 70]	$f_0=30$ $f_1=35$ $f_2=44$ $f_3=51$ $f_4=63$ $f_5=67$	$f_0=30$ $f_1=35$ $f_2=44$ $f_3=51$ $f_4=63$	$f_0=30$ $f_1=35$ $f_2=44$ $f_3=51$ $f_4=63$

III.4 Conclusion

In this chapter, we design smart materials using metamaterials. These materials are modeled as matrices with varying numbers of elements (4x4 cells). A supercell is a periodic arrangement of identical units of two different types (A or B) that can be controlled by an external switching system. Our research focuses on controlling the behavior of materials by diluting type A supercells with type B cells.

We can conclude that if the majority of cells are conductors like proven by cases 4,6, then the comportment is conductor. And if the majority of cells is dielectric as we observed in cases 5,7, then the comportment is dielectric.

We can conclude also in the cases 50% connected and 50% disconnected that every case with their opposite give us the same comportment.

The position of cells it has no effect on comportment the difference from the point of view.

General conclusion

Metamaterials are a large family of metallo-dielectric structures with specific electromagnetic properties. By varying periodicity and/or LC contribution in each elementary cell, different combinations of electric properties can be derived (ENG, MNG and DNG). Such versatility is exploited in several conventional applications (antennas, filters, delay-lines, etc.) but it also suggested new ones like cloaking. Strong research efforts were dedicated on realization techniques that mainly aim to miniaturization and broad angular/bandwidth response. Several features make manufactured metamaterials limited or different than ideal references. These are mostly due to the truncation of the periodicity and a non-omnidirectional behavior. Applications of metamaterials are still under development although at lower pace compared to 10 years ago. From an engineering perspective, metamaterial-enhanced antenna design is mature for practical purposes and commercial outcomes especially in defense applications where size-constraints can be largely compromised. In other engineering sectors the gap between manufacturing outcomes and expected behavior is still large and this discourages short-term commercial initiatives.

In this dissertation and as a first step we designed a structure of metamaterial super cell with two different behaviors type A and type B. The smart materials supercell is designed using HFSS software (simulation and professional modeling tool). The study investigates the effect of dilution of type B metamaterial in a type A one and vice versa. We started with a supercell composed fully with a metamaterial of type A or type B (100 % type A metamaterial or 100 % type B metamaterial), and gradually added and diluted these materials with a type B metamaterial. The added portion of type B metamaterial grows from a small portion to the full amount of metamaterial (100 % type B). We find that the behavior of metamaterial supercells depends on the proportion of the number of one type (A or B) of unit cells relative to the other type that makes up the supercell. If the number of type A unit cells is greater than the number of type B unit cells, the behavior of the supercell mainly follows that of the type A metamaterial, and vice versa.

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Abstract:

Metamaterials are composite materials that are tailored to respond to desired electromagnetic properties that are not found in nature. In this work, smart materials based on metamaterial are designed. These smart materials are modeled as supercells with metamaterial unit cells of two types that are controlled by an external switching system. The first type is a connected metamaterial super cell that behaves as a conductor, following the permittivity the Drude frequency dependent model, and has a refractive index near to zero. While the second type is a disconnected metamaterial super cell that behaves as a dielectric medium with refractive index greater than unity, and permittivity following the Lorentz frequency dependent model. At the beginning we select the supercell as 100 % of one of the two types and then dilute it by the second type gradually, resulting in a supercell involving both behaviors at the same time in different frequency ranges, which can be applied in many areas including antennas. This study was done using HFSS simulation software.

Key words: Metamaterials, Smart materials.

المخلص:

المواد الخارقة هي مواد مركبة تم تصميمها للاستجابة لخصائص كهرومغناطيسية معينة لا توجد في الطبيعة. في هذا العمل، تم تصميم مواد ذكية تعتمد على المواد الخارقة. تم نمذجة هذه المواد الذكية كخلايا فائقة تحتوي على خلايا وحدة من نوعين يتم التحكم بها بواسطة نظام تبديل خارجي. النوع الأول هو خلية فائقة متصلة تتصرف كموصل، وتتبنى نموذج السماحية الذي يعتمد على تردد درود، ولها معامل انكسار قريب من الصفر. بينما النوع الثاني هو خلية فائقة غير متصلة تتصرف كوسط عازل بمعامل انكسار أكبر من الواحد، وتتبع السماحية نموذج يعتمد على تردد لورنتز. في البداية، نختار الخلية الفائقة لتكون 100% من أحد النوعين، ثم نخففها بالنوع الثاني تدريجيًا، مما ينتج خلية فائقة تشمل السلوكيات الاثنين في نفس الوقت في نطاقات تردد مختلفة، والتي يمكن تطبيقها في العديد من المجالات بما في ذلك الهوائيات. تمت هذه الدراسة باستخدام برنامج محاكاة HFSS.

الكلمات المفتاحية: المواد الخارقة، المواد الذكية.

Résumé:

Les métamatériaux sont des matériaux composites conçus pour répondre à des propriétés électromagnétiques souhaitées qui ne se trouvent pas dans la nature. Dans ce travail, des matériaux intelligents basés sur les métamatériaux sont conçus. Ces matériaux intelligents sont modélisés sous forme de supercellules composées de deux types de cellules unitaires de métamatériaux contrôlées par un système de commutation externe. Le premier type est une supercellule de métamatériaux connectée qui se comporte comme un conducteur, suivant le modèle dépendant de la fréquence de Drude pour la permittivité, et ayant un indice de réfraction proche de zéro. Le second type est une supercellule de métamatériaux déconnectée qui se comporte comme un milieu diélectrique avec un indice de réfraction supérieur à l'unité, et une permittivité suivant le modèle dépendant de la fréquence de Lorentz. Au début, nous sélectionnons la supercellule comme étant constituée à 100 % de l'un des deux types, puis nous la diluons progressivement avec le second type, ce qui donne une supercellule présentant les deux comportements en même temps dans différentes gammes de fréquences. Cette configuration peut être appliquée dans de nombreux domaines, y compris les antennes. Cette étude a été réalisée en utilisant le logiciel de simulation HFSS.

Mots clés: Metamateriaux, matériaux intelligents.