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Design and simulation of a metasurface absorber for THz applications

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وأهدي ثمرة هذا الجهد المتواضع لأولئك الذين كانوا سبب وجودي وسندا لحياتي

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قروي ثابت

Abstract

- This thesis aims to design and simulate a terahertz superabsorbent surface using graphene, based on a three-layer structure consisting of a metallic layer, an insulating layer, and a tunable graphene layer. Ansys Lumerical software and the Finit-Dimensional Time Domain method were used to investigate the absorption, reflection, and transmittance properties. The results showed high absorption between 1.5 and 4 terahertz with very low reflection and transmittance. The study also demonstrated that varying the chemical potential, structural dimensions, and insulating layer thickness directly affects the resonant frequency and absorption efficiency, making the graphene-based metasurface absorber a promising solution for communications, sensing, and electromagnetic detection applications.

- Keywords: metasurfaces, metamaterials, terahertz absorber, graphene, electromagnetic Waves, terahertz range, electromagnetic absorption, resonance, reflectance coefficient, transmittance. Ansys Lumerical software

ملخص

تهدف هذه الأطروحة إلى تصميم ومحاكاة سطح فائق الامتصاص في نطاق الترددات تيراهيرتز باستخدام الجرافين، وذلك بالاعتماد على بنية ثلاثية الطبقات تتكون من طبقة معدنية، وطبقة عازلة، وطبقة جرافين قابلة للضبط. استُخدم برنامج Ansys Lumericalوطريقة FDTD لدراسة خصائص الامتصاص والانعكاس والنفاذية. أظهرت النتائج امتصاصًا عاليًا بين 1.5 و4 تيراهيرتز مع انعكاس ونفاذية منخفضين للغاية. كما أوضحت الدراسة أن تغيير الجهد الكيميائي والأبعاد الهيكلية وسُمك الطبقة العازلة يؤثر بشكل مباشر على تردد الرنين وكفاءة الامتصاص، مما يجعل المواد فائقة الامتصاص القائمة على الجرافين حلاً واعدًا لتطبيقات الاتصالات والاستشعار والكشف الكهرومغناطيسي

الكلمات المفتاحية: السطح الفائق، المادة الفائقة، ممتص موجات تيراهيرتز، الجرافين، الموجات الكهرومغناطيسية، نطاق تيراهيرتز، الامتصاص الكهرومغناطيسي، الرنين، معامل الانعكاس والنفاذية , برنامج ansys lumerical

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General Introduction

General Introduction

With the rapid development of modern communication technologies and electronic systems, terahertz (THz) frequency applications have become a major focus in scientific and industrial fields. Located between microwaves and infrared radiation within the electromagnetic spectrum, the terahertz frequency range possesses unique properties that make it suitable for numerous advanced applications, such as ultrafast communications, medical imaging, detection and security systems, advanced radar, and various sensing applications. Despite the immense potential of terahertz waves, their effective control and utilization still face several challenges, including high losses and the difficulty of designing components capable of precisely controlling the propagation of electromagnetic waves within this frequency range. Therefore, researchers have turned to metamaterials and metasurfaces as innovative technologies capable of controlling electromagnetic properties in unconventional ways. Absorbing metasurfaces are among the most important applications of metamaterials, as they are characterized by their ability to almost completely absorb incident waves at specific frequencies. Furthermore, they can be integrated into many modern electronic and optical devices. In this context, this thesis aims to design and simulate a superabsorbent surface specifically designed for terahertz frequency applications, study its electromagnetic properties, and analyze the effect of various engineering parameters and material properties on its absorption ratio. The simulation was performed using Ansys Lumerical software and the FDTD FDTD method, one of the most widely used techniques for analyzing high-frequency electromagnetic structures. Furthermore, this work aims to optimize the performance of the proposed structure to achieve high absorption in the terahertz frequency range, while maintaining a simple and compact design suitable for modern electromagnetic communication, sensing, and detection applications.

Chapter I : Electromagnetic waves

1. Introduction

Electromagnetic waves are considered the backbone of most modern communications technologies. They are a way to transmit information across vast distances without physical means. To understand these waves, we begin with Maxwell’s equations, a comprehensive set of equations that describe electromagnetic phenomena. From these equations, we derive the wave equation describing their propagation in various media.

When we study reflection and transmission, we examine how waves interact with materials, which is important for the design of antennas and wireless systems. The electromagnetic spectrum extends from radio waves to gamma rays, opening up new avenues for developing next-generation wireless communication technologies.

2. Maxwell's equations

Four mathematical equations are considered the basic constituents of electromagnetism and were collected by Scottish scientist James Clerk Maxwell in the late nineteenth century. It describes the behavior of electric and magnetic fields, explains how charges and currents produce these fields, predicts the existence of electromagnetic waves, and, importantly, they are the basis of all modern communication technologies (radio, television, mobile, Wi-Fi).

These equations have two forms: the first is the differential equation, which relates electric fields to their sources, called charge density, and is used in static electricity and static magnetic fields. The second form, the integral equation, relates the sources to the current density and is used in the case of time-varying electric and magnetic fields. [1]

1) The first equation: Gauss' law of electricity. This law is considered one of the most important laws in the study of static electricity .Where the total electric flux (ψ) through any closed surface is equal to the sum of the electric charges within that surface (S). [1]

- We have the following differential shape: [1]

$$\oint_S \vec{E} \cdot \overrightarrow{dS} = \frac{Q_{enc}}{\varepsilon_0} \quad (1)$$

- But we have the charge density, and we express it by: [1]

$$Q_{enc} = \int_V \rho_v dv \quad (2)$$

- So, Gauss's law becomes: [1]

$$\oint_S E \cdot dA = \int_V (\nabla \cdot E)\, dv \quad (3)$$

- Then we find: [1]

$$\vec{\nabla} \cdot \vec{E} = \frac{\rho_v}{\varepsilon_0} (4)$$

- It is called the permittivity of the void. [1]

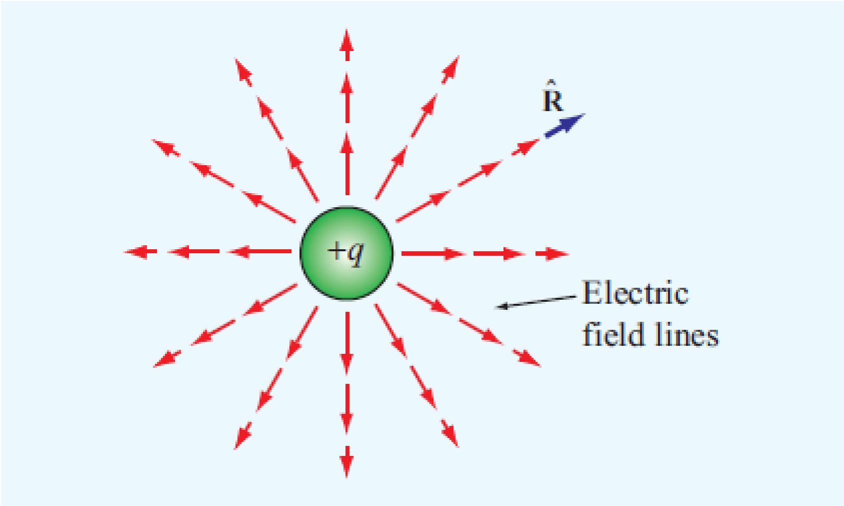

Figure 1.1: Electric Field Lines around a Positive Point Charge [1]

- Applying Gauss's law to calculate the electric field involves determining whether symmetry exists.

2) The second equation: Gauss' law of magnetism

This equation tells us that there are no individual magnetic charges (monopoles). [1]

- We have the following differential shape: [1]

$$\oint_S \vec{D} \cdot \vec{dS} = 0 \quad (5)$$

- Using Gaussian divergence theory to transform the surface integral of the electric [1] field into a volumetric integral of the field divergence, we find: [1]

$$\oint_S \vec{D} \cdot \vec{dS} = \int_v \vec{\nabla} \cdot \vec{D} dv = 0 \quad (6)$$

- Or: $\vec{\nabla} \times \vec{E} = 0$

- When: $\vec{B} = \mu_0 \vec{H} \mid \ \mu_0 = 4\pi \times 10^{-7} (H \backslash m)$

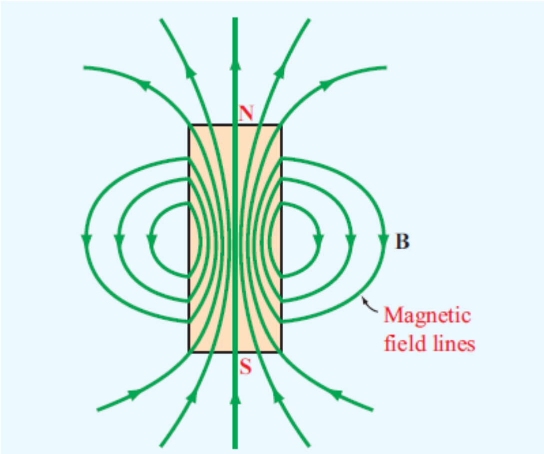

Figure1.2: Magnetic Field Lines around a Bar Magnet [1]

3) The third equation: Faraday's law

This equation tells us that a magnetic field changing with time generates an electric field. In the first experiment, we have a direct case of kinetic electromotive force [1]; according to the flux law, we find that: [1]

$$\varepsilon = -\frac{d\Phi}{dt} \tag{7}$$

- Through the electric field explaining the electromotive force, if the electromotive force (as Faraday experimentally found) is equal to the rate of change of flux [1], then:

$$\varepsilon = \oint_L \vec{E} \cdot \overrightarrow{dl} = \frac{d\Phi}{dt} \tag{8}$$

- Then **E** is related to the change in **B** by the equation: [1]

$$\oint_L \vec{E} \cdot \overrightarrow{dl} = -\frac{d}{dt}\int_S \vec{B} \cdot \overrightarrow{dS} \tag{9}$$

- This represents Faraday's law in its integral form, which we can transform into a differential form by applying Stokes' theorem: [1]

$$\vec{\nabla} \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \tag{10}$$

4) Fourth equation: Ampere-Maxwell law

- Initially, Ampere's law was written in differential form as [3]:

$$\nabla \times B = \mu_0 J \qquad (11)$$

- This means that the magnetic spin (Curl) of the magnetic field H is equal to the electric current density J. [3]

- When taking the divergence for this equation $\vec{\nabla} \cdot \vec{j} = -\frac{\partial \rho_v}{\partial t} = -\partial/\partial t\,(\varepsilon_0 \nabla \cdot E) = -\nabla \cdot (\varepsilon_0\, \partial E / \partial t)$ [3], that is ∇·, J must be zero. But from the current continuity equation, we note that $\nabla \cdot j \neq 0$ [3]:

$$\vec{\nabla} \cdot \vec{j} = -\frac{\partial \rho_v}{\partial t} \qquad (12)$$

- By applying Hertz's experiments on electromagnetic waves in 1888, Maxwell found a way to modify Ampere's law, where Maxwell called the additional term **the displacement current.** [3]

$$\vec{J}_d = \varepsilon_0 \frac{d\vec{E}}{dt} \qquad (13)$$

- The law will then take the following integrated form. [3]:

$$\oint_L \vec{B} \cdot \vec{dl} = \mu_0 \left(I + \varepsilon_0 \frac{d}{dt} \int_S \vec{E} \cdot \vec{dS} \right) = \mu_0 \left(\int_S \vec{J} \cdot \vec{dS} + \varepsilon_0 \frac{d}{dt} \int_S \vec{E} \cdot \vec{dS} \right) \qquad (14)$$

- Applying Stokes' theorem to the integral equation, we find. [3]:

$$\oint \vec{B} \cdot \vec{dl} = \int_s (\vec{\nabla} \times \vec{B}) \vec{dS} \qquad (15)$$

- Integral plus s of Substituting it into the law, we obtain. [3]:

$$\int_s (\vec{\nabla} \times \vec{B}) dA = \mu_0 \int_s \vec{J} \cdot \vec{dS} + \mu_0 \epsilon_0 \frac{\partial}{\partial t} \int_s \vec{E} \cdot \vec{dS} \qquad (16)$$

- Let's find the following differential form. [3]:

$$\vec{\nabla} \cdot \vec{B} = \mu_0 \left(\vec{J} + \varepsilon_0 \frac{d\vec{E}}{dt} \right) \tag{17}$$

- In the last section, we put the finishing touches on Maxwell's equations. [1]:

Gauss's law of electricity	$\vec{\nabla} \cdot \vec{E} = \frac{\rho_v}{\varepsilon_0}$
Gauss's law of magnetism	$\vec{\nabla} \times \vec{E} = 0$
Faraday's law	$\vec{\nabla} \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$
Ampere-Maxwell law	$\vec{\nabla} \times \vec{B} = \mu_0 \left(\vec{J} + \varepsilon_0 \frac{d\vec{E}}{dt} \right)$

Table 1.1: Summary of Maxwell's Equations

Maxwell's equations are the backbone of electromagnetic waves, explaining how they originate, propagate, travel at the speed of light in a vacuum, and generate magnetic fields. [1]

3. Wave equation

Waves are oscillations that occur in a balanced manner in both electric and magnetic fields, and propagate through space at the speed of light. What distinguishes these waves is that they do not require a physical medium to propagate, making them ideal for use in telecommunications applications. Waves are generated when there is a change in the electric or magnetic field, as described in Maxwell's equations. [2] From Maxwell's equations, specifically equations three and four, we see that they are related differential equations; in other words, the electric field (E) and the magnetic field. [2] (B) They are part of a single equation that can be separated by applying spin to them. Assuming that the charge density (∇·E) = 0 and the current (∇·B) = 0, we find the final result. [2]:

$$\nabla^2 \vec{E} = \mu_0 \epsilon_0 \frac{\partial^2 \vec{E}}{\partial t^2} \;\Big|\; \nabla^2 \vec{B} = \mu_0 \epsilon_0 \frac{\partial^2 \vec{B}}{\partial t^2} \tag{18}$$

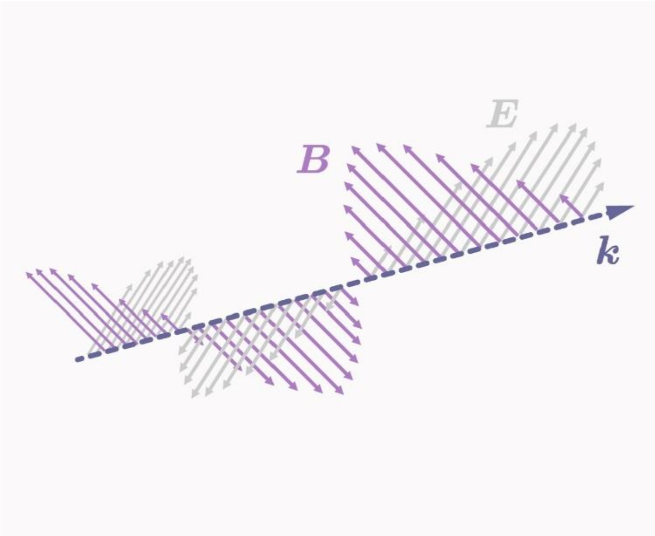

Figure 1.3: Propagation of a Plane Electromagnetic Wave [1]

- After applying the curl, we obtain two separate equations for E and B of the second degree in space, where each Cartesian component of E and B satisfies **the three-dimensional wave equation**. [2]

$$\nabla^2 \vec{E} = \frac{1}{v_p^2} \frac{\partial^2 \vec{E}}{\partial t^2} \quad (19)$$

- To determine if we have a wave equation, we match it to the general form of the wave equation and find. [2]:

$$\frac{1}{v_p^2} = \mu_0 \epsilon_0 \quad (20)$$

- From this match, we can deduce the wave speed, which is as follows [2]:

$$c = \frac{1}{\sqrt{\mu_0 \epsilon_0}} \quad (21)$$

- Both μ_0 and ϵ_0 physical constants whose values we know; if we input the values, we get a specific value [2]:

$$\vartheta_p = 3 \cdot 10^8 m / s \quad (22)$$

- From this, we conclude that the speed of the wave is equal to the speed of light, $\vartheta_p = c$. can express our wave equation in terms of the speed of light. [2]:

$$\nabla^2\vec{E} = \frac{1}{C^2}\frac{\partial^2\vec{E}}{\partial t^2} \tag{23}$$

- Let's take a look at the structure of the wave equation; we find that it consists of two important parts, which are. [2]:

- $\nabla^2\vec{E}$: The spatial change of the wave represents. [2]

- $\frac{\partial^2\vec{E}}{\partial t^2}$: The time change of the wave represents. [2]

Using the wave equation, we can understand the propagation of electromagnetic waves, which is extremely important for studying phenomena such as reflection, transmission, and absorption in advanced materials such as Metasurfaces absorbers [2].

4. Electromagnetic spectrum

The electromagnetic spectrum is the complete distribution of electromagnetic waves by frequency or wavelength. This spectrum includes all types of waves, from low-frequency radio waves to high-frequency gamma rays. Each range in this spectrum is characterized by different physical properties and technical applications. [4]

1) General Characteristics of the Spectrum

- The higher the frequency, the higher the energy and the shorter the wavelength. [4]
- Low-frequency waves (such as radio) travel long distances and penetrate barriers. [4]
- High-frequency waves (such as X-rays) have high penetrating power but can be biologically harmful. [4]

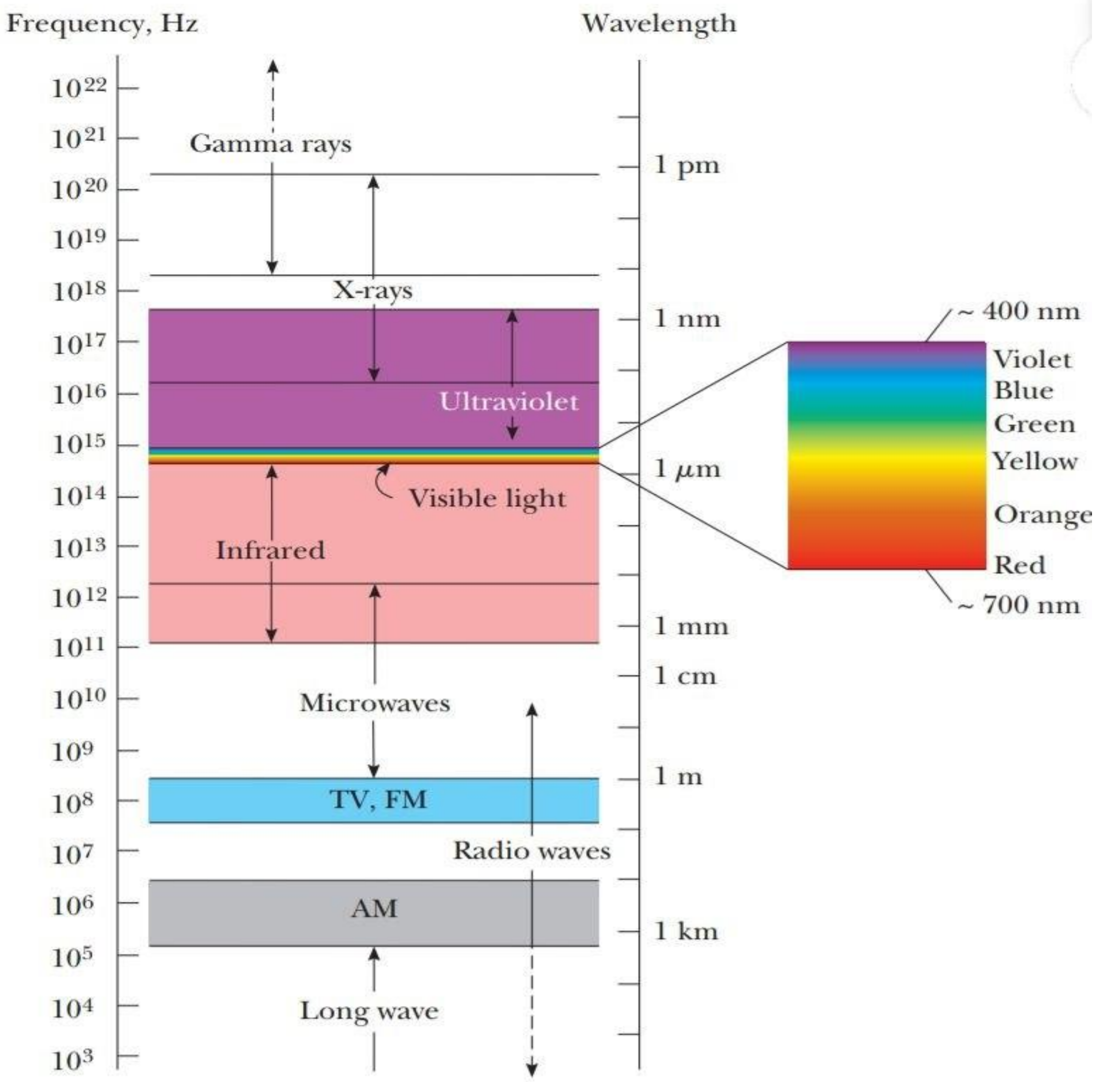

Figure 1.4: The Electromagnetic Spectrum [4]

2) Types of the electromagnetic spectrum

- **Radio waves:** whose wavelengths range from more than 10^4 m to about 0.1 m, are the result of charges accelerating through conducting wires. They are generated by such electronic devices as *LC* oscillators and are used in radio and television communication systems. [4]
- **Microwaves:** have wavelengths ranging from approximately 0.3 m to 10^{-4} m and are also generated by electronic devices. Because of their short wavelengths, they are well-suited for radar systems and for studying the atomic and molecular properties of matter. Microwave ovens are an interesting domestic application of these waves [4]

- **Infrared waves:** have wavelengths ranging from approximately 10^{-3} m to the longest wavelength of visible light, 7.10^{-7}m. These waves, produced by molecules and room-temperature objects, are readily absorbed by most materials. Infrared radiation has practical and scientific applications in many areas, including physical therapy, IR photography, and vibrational spectroscopy. [4]

- **Visible light:** Visible light is the part of the electromagnetic spectrum that the human eye can perceive. The wavelengths of visible light, which correspond to different colors, range from red (7 × 10^{-7} m) to violet (4 × 10^{-7} m), peaking at a wavelength of approximately 5.5 × 10^{-7} m. Light is a fundamental element in optics and optical instruments and is used in numerous fields, including Education, scientific research, the development of optical technologies, and medicine in medical diagnostic devices. [4]
- **Ultraviolet waves**: Their wavelengths range between $[10^{-7}]$ and $[10^{-10}]$, and it extends beyond visible light. These rays are capable of affecting cells and materials, but they are invisible to the human eye and originate from the sun. They are produced as a result of high-energy emissions and nuclear reactions occurring within the sun. Despite their benefits, they can cause some diseases and skin burns. However, they are used in numerous fields such as sterilization, chemical analysis, and medicine. [4]
- **X-rays**: have wavelengths in the range from approximately 10^{-8} m to 10^{-12} m. The most common source of X-rays is the stopping of high-energy electrons upon bombarding a metal target. X-rays are used as a diagnostic tool in medicine and as a treatment for certain forms of cancer. X-rays are also used in the study of crystal structure because X-ray wavelengths are comparable to the atomic separation distances in solids (about 0.1 nm). [4]
- **Gamma rays** are electromagnetic waves emitted by radioactive nuclei (such as 60Co and 137Cs) and during certain nuclear reactions. They have wavelengths ranging from approximately10^{-10} m to less than 10^{-14} m. Gamma rays are highly penetrating and produce serious damage when absorbed by living tissues. [4]

5. Reflection and transmission

When an electromagnetic wave strikes the boundary between two media with different electromagnetic properties, such as permittivity and permeability, part of the wave is reflected back into the first medium, a phenomenon known as reflection, while the other part is transmitted into the second medium, a phenomenon known as transmission. However, when analyzing this phenomenon, different scenarios are studied [2]:

1) Normal Incidence

In this case, we study normal incidence, where the wave is incident perpendicularly on the interface between the two media. Babel allows us to express the electric field of the incident, reflected, and transmitted waves using the following equations [2]:

$E_I = E_{0I} e^{i(k_1 z - \omega t)} \Longrightarrow$ the incident wave [2]

$E_R = E_{0_R} e^{i(-k_1 z - \omega t)} \Longrightarrow \Gamma = \frac{E_R}{E_I} = \frac{\eta_2 - \eta_1}{\eta_2 + \eta_1} \Longrightarrow$ the reflected wave [2]

$E_T = E_{0_T} e^{i(-k_2 z - \omega t)} \Longrightarrow \mathrm{T} = \frac{E_T}{E_I} = \frac{2\,\eta_2}{\eta_2 + \eta_1} \Longrightarrow$The transmitted wave, Where Intermediate resistance is [2]:

$$\eta = \sqrt{\frac{\mu}{\epsilon}} \qquad (24)$$

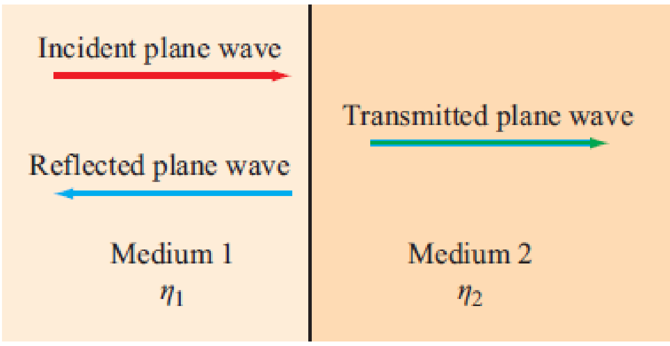

Figure 1.5: Electromagnetic Wave Interaction at the Interface between Two Media [2]

- R and T are called the reflection and transmittance coefficients, respectively, and their role is to measure the ratio of incident energy that is reflected and transmitted. The relationship between these coefficients is expressed as [2]:

$$1 + \Gamma = \mathrm{T} \quad | \quad \mathrm{R} + \mathrm{T} = 1 \qquad (25)$$

$$\text{With: } \Gamma = \frac{\eta_2 - \eta_1}{\eta_2 + \eta_1}, \ \mathrm{T} = \frac{2\eta_2}{\eta_2 + \eta_1} \qquad (26)$$

2) Oblique incidence

In this section, we study wave propagation from two media with different angles, as these angles play a crucial role in determining the wave's direction of propagation. However, if the wave strikes the interface between the two media at an angle not perpendicular to the surface, it is known as oblique incidence and is divided into two parts: a reflected part and a refracted part [1]

In this case, we will see three laws that influence the behavior of electromagnetic waves [1]:

- **First low: The plane of incidence**

Incident, reflected, and transmitted waves have a plane known as the plane of incidence, which also includes the normal. It is expressed by the following equation [1].

$$k_I \sin\theta_I = k_R \sin\theta_R = k_T \sin\theta_T \quad (27)$$

θ_I = the angle of incidence [1]

θ_R = the angle of reflection [1]

θ_T = the angle of transmission [1]

- **Second law: law of reflection.**

The angle of incidence is equal to the angle of reflection [1]:

$$\theta_I = \theta_R \quad (28)$$

- **Third law: law of refraction—Snell's law**

From Snell's law, we can derive the relationship between the angle of incidence and the angle of refraction, which is given by the following equation [1]:

$$\frac{\sin\theta_T}{\sin\theta_I} = \frac{n_1}{n_2} \quad (29)$$

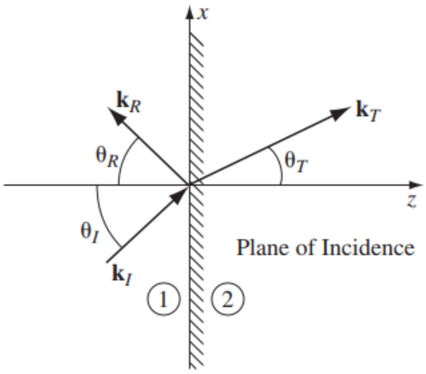

Figure 1.6: Oblique incidence of an electromagnetic wave at the interface between two media, showing reflection and transmission angles [1]

Polarized waves are divided into two types: Transverse electric (TE) and transverse magnetic (TM) [1]

3) Polarization

Electromagnetic wave polarization is a physical phenomenon that describes the direction of oscillation of the electric field of a transverse wave relative to its direction of propagation. In this case, the wave's oscillation is confined to a single plane or a defined path. Polarization is an exclusive property of transverse waves (such as light), and its direction is determined by the vector parallel to the electric field. The main types of polarization are linear, circular, and elliptical [3].

- Types of Electromagnetic Wave Polarization [3]:

- **Linear Polarization**: In this type, the wave oscillates in a straight line or a single plane along the direction of propagation [3].

- **Circular Polarization**: The electric field of the wave moves in a circular pattern with time, and the amplitude is constant. It can be circular to the right or left [3].

- **Elliptical Polarization**: This is the general case where the electric field follows an elliptical path. It results from the combination of two perpendicular linear waves of unequal amplitude and phase shift [3].

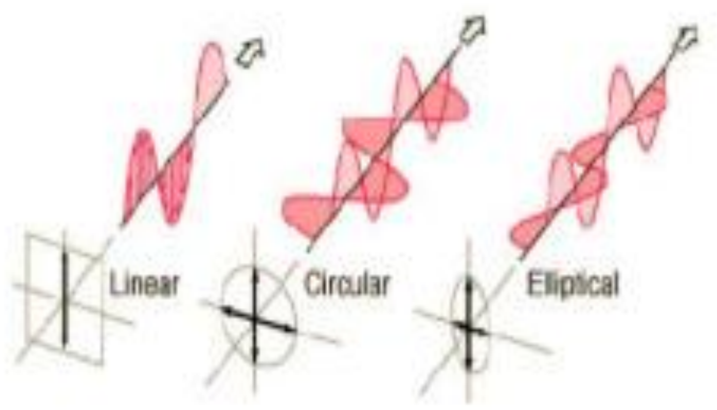

Figure 1.7: Types of electromagnetic wave polarization: linear, circular, and elliptical polarization [1]

6. Brewster angle

For all the energy of the incident wave to be transferred to the second medium and the reflected wave to be absent, the reflection coefficient must become zero for parallel polarization. For this to happen, the reflected and transmitted waves must be perpendicular, and this angle is called the Brewster angle. Through Snell's law, the Brewster angle is given by the following relationship [1]: $tan\,\theta_B \cong \frac{n_2}{n_1}$ (30)

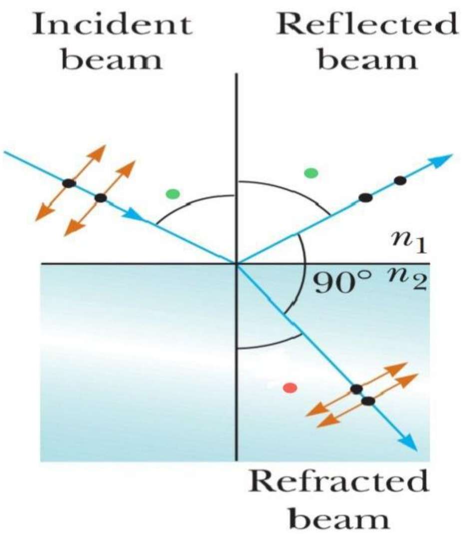

Figure 1.8: Brewster angle showing incident, reflected, and refracted beams at the interface between two media [6]

7. Conclusion

This chapter addressed the theoretical foundations of electromagnetic waves, starting with Maxwell's equations, which form the mathematical framework for understanding electromagnetic field behavior, leading to the derivation of the wave equation and the analysis of propagation characteristics in vacuum and materials. The phenomena of reflection and transmission at the boundaries of different media were also discussed, highlighting their importance in the design of communication systems. We then reviewed the electromagnetic spectrum, its divisions, and emphasized the physical characteristics and practical applications of each band. At the end of the chapter, special focus was given to terahertz waves, which represent a promising avenue for future communication technologies due to their high spectral bandwidth and diverse applications.

This theoretical framework paves the way for the second chapter, which will discuss in detail electromagnetic materials, especially absorbers and metamaterials, and their role in controlling wave propagation and improving the performance of communication systems.

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Chapter II : Metamaterial absorbers

1. Introduction :

Metamaterials are artificial composite materials with electromagnetic properties beyond those found in nature. The term " metamaterials was introduced by R. M. Walser. In analogy with the natural materials, metamaterials generally are composed of periodic or non-periodic subwavelength “meta-atom”. By reasonably designing the meta-atoms as required and flexibly arranging them, bulky metamaterials can not only mimic known material responses but also tailor new, physically realizable responses, such as negative permittivity and permeability, zero refractive index, etc. Metasurfaces, as the two-dimensional counterparts of volumetric metamaterials, offer advantages such as lower loss and easier fabrication, and can be engineered to control electromagnetic fields, including wavefront transformation and polarization conversion. Metamaterials, including Metasurfaces, are expected to achieve significant technological breakthroughs in the areas of new microwave/optical device design, broadband/miniaturized antenna design, high-resolution imaging, novel sensors, switches and modulators, military cloaks, and absorbing materials. [1]

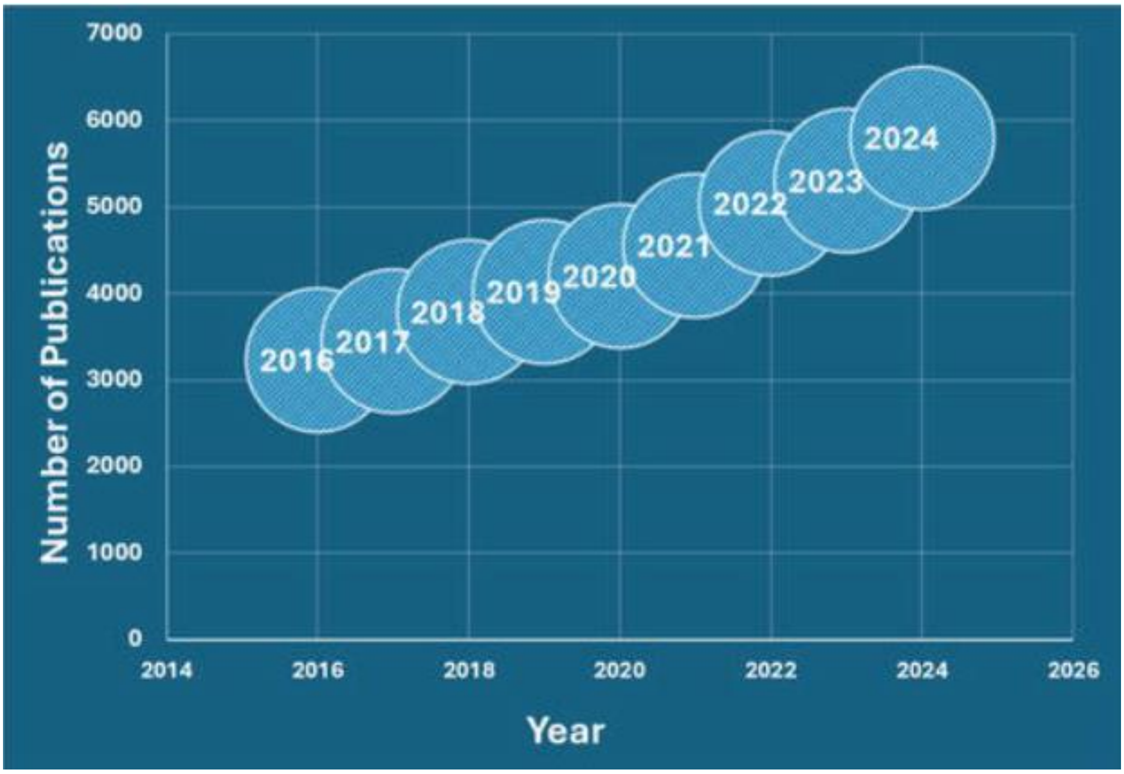

Figure 2.1: General concept of metamaterials and Metasurfaces [4]

2. Metamaterials :

1) Definition: Metamaterials are structures and properties not found in nature, and are highly valued for their unique electromagnetic properties. The name "metamaterials" derives from the Greek word "meta," meaning "beyond" or "after," and the Latin word "materia" meaning "matter," thus signifying their essence as something beyond ordinary matter. These materials are engineered by arranging microscopic structures in specific patterns to control electromagnetic waves, sound waves, or other physical phenomena in unconventional ways [1]

2) Types of Metamaterials

- Metamaterials are classified based on permittivity and permeability. We mention several types, including the first type: double-positive materials (DPS), or, in other words, right-handed metamaterials, which require both permittivity and permeability to be positive simultaneously (i.e., $\varepsilon > 0$, $\mu > 0$). [4]
- The second type has a permittivity less than zero and a permeability greater than zero. This type is called an epsilon-negative (ENG), in which, in certain frequency ranges, it exhibits properties similar to those of natural materials such as plasma, doped semiconductors, and others. [4]
- The third type exhibits opposite properties in permittivity and permeability ($\varepsilon > 0$, $\mu < 0$). It is characterized by negative magnetic permeability, a property of paramagnetic materials that appears in specific frequency ranges, particularly in gyromagnetic or ferrimagnetic materials. [4]
- When both the electrical permittivity and magnetic permeability are negative (i.e., $\varepsilon < 0$, $\mu < 0$), we call this type, which is the fourth type, a double-negative (DNG) material or a left-handed metamaterial. This type only exists through artificial synthesis and is not found in nature. [4]

- To obtain metamaterials with near-zero or zero refractive index, either the electrical permittivity or magnetic permeability, or both, must approach zero. [4]

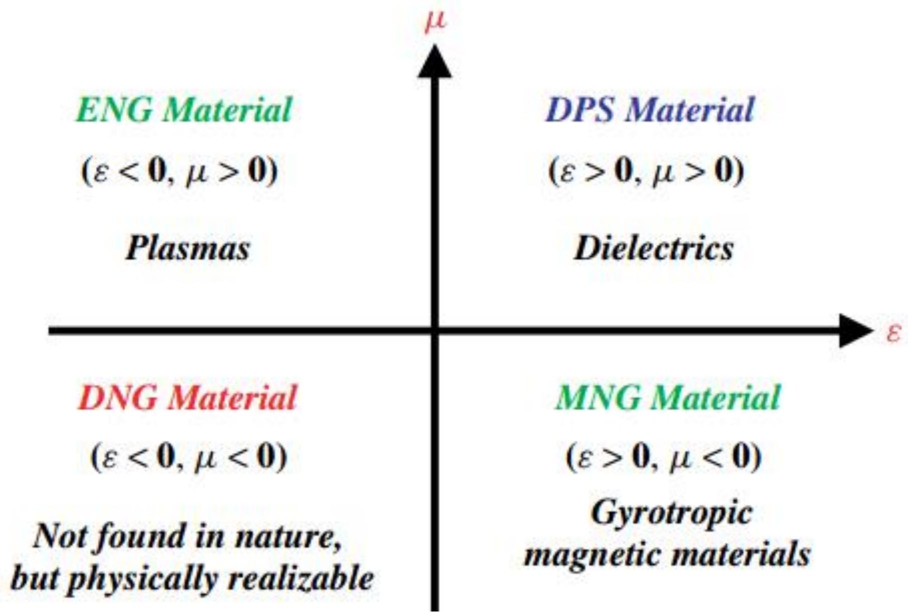

Figure 2.2: Design and Analysis of Metamaterial Using Permittivity and Permeability Properties [4]

3) Metamaterials properties: The growing interest in metamaterials and their applications in various fields and industries is due to the unique properties they possess compared to natural materials. [11]

- In 1968, Veselago provided the theoretical definition of a new class of materials with unconventional properties, such as a negative refractive index, negative electrical permeability, negative phase and group velocities, inverse Doppler shift, and inverse Cherenkov radiation. Since no naturally occurring materials with these properties existed, studies on the subject remained neglected until 1996. At that time, Pendry and others proposed the design and behavior of synthetic materials known as metallic microstructures. These materials consist of a periodic arrangement of infinite wires in a cubic lattice, exhibiting negative electrical permeability (ε), and slit-ring resonant structures (SRRs), exhibiting negative permeability (μ). By 1998, John Pendry had identified a practical method for creating materials with a negative refractive index (LHM) without resorting to the traditional right-hand rule. His team published research demonstrating a composite structure comprising a periodic array of subwavelength metallic wires that can exhibit negative refractive index properties at microwave frequencies, thereby facilitating the practical application of metamaterials. Other researchers have also successfully created a composite medium that simultaneously exhibits negative effective permeability (μ_{eff}) and negative electrical permeability (ε_{eff}) at microwave frequencies. This medium, composed of a periodic array of slit-ring resonators (SRRs) and interconnected microwires, is known as a negative refractive index medium [11]

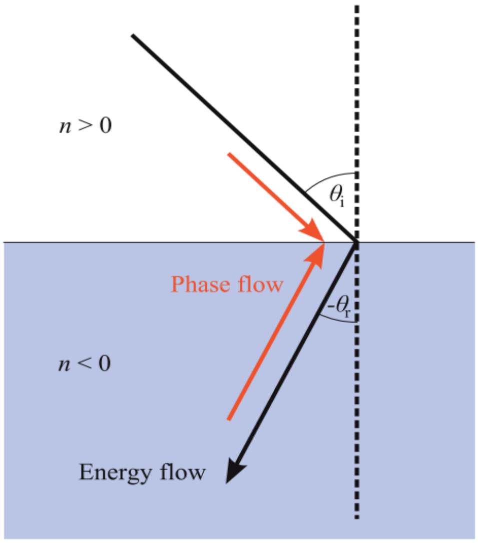

Figure 2.3: Negative refraction: light passing from a medium with $n > 0$ to one in which $n < 0$.[11]

- This type of material is considered an artificial material whose properties are derived from a subwavelength geometric structure, not just its chemical composition. The requirement that the structure be smaller than the wavelength is essential and distinguishes metamaterials from photonic crystals, whose structures are on the same wavelength scale. The structural elements that make up metamaterials are periodic, but not necessarily so; they are often resonant, though this is not required. Metamaterials take advantage of light scattering. The power of metamaterials lies in the responsiveness of these complex structures. They can be represented by a very small number of relatively simple parameters. The behavior of light in natural materials is usually described by relating it to their properties, such as the dielectric permittivity ε and the magnetic permeability μ at any given frequency. The equations take the form of generalized linear coefficients with two parameters. The two dimensionless tensors ξ and ζ describe any rotational effect of the electromagnetic coupling. As with ε and μ, these fields can be composite, highlighting potential phase differences between them, and they vary with frequency. These properties are manifested in the formative equations that relate the two derived fields D and H to the total electric and magnetic fields E and B [11]

$$D = \varepsilon_0 \varepsilon E + \sqrt{\varepsilon_0 \mu_0} \xi H \quad (1)$$

$$B = \mu 0 \mu H + \sqrt{\varepsilon 0 \mu 0} \zeta E \quad (2)$$

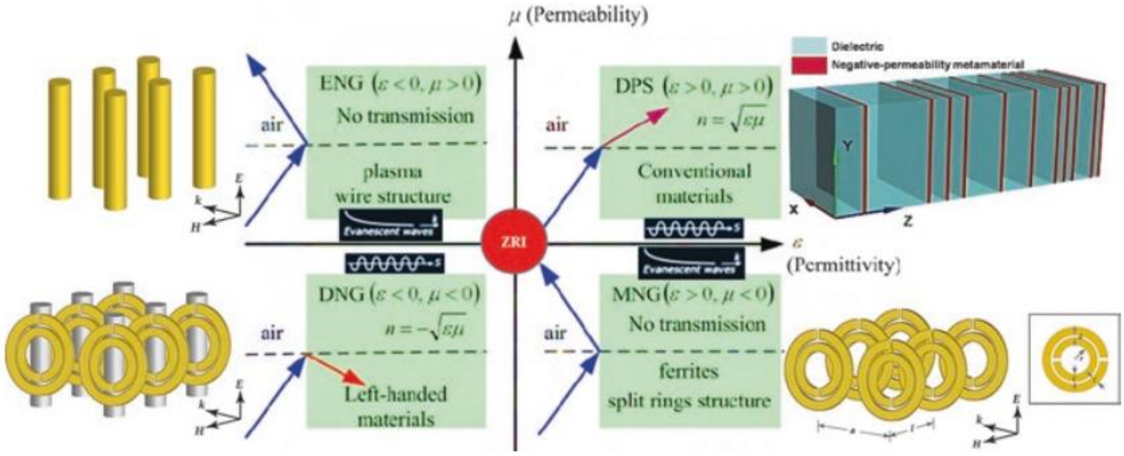

Figure 2.4: Classification of electromagnetic metamaterials on the basis of permeability (μ) and permittivity (ε)[11]

- The fabrication of materials used in organic materials focuses on various split-ring resonator (SRR) structures. These resonators become efficient capacitor-inductance circuits when integrated into a resonant system by adjusting their capacitance (C) or inductance (L), thereby modulating the resonant frequency to achieve w = 1/LC. Using these resonators, also known as electric field-coupled LC (ELC) resonators, electrically tunable devices are obtained—that is, devices that can be tuned using an external voltage by moving them towards the blue or red end of the frequency spectrum [11]

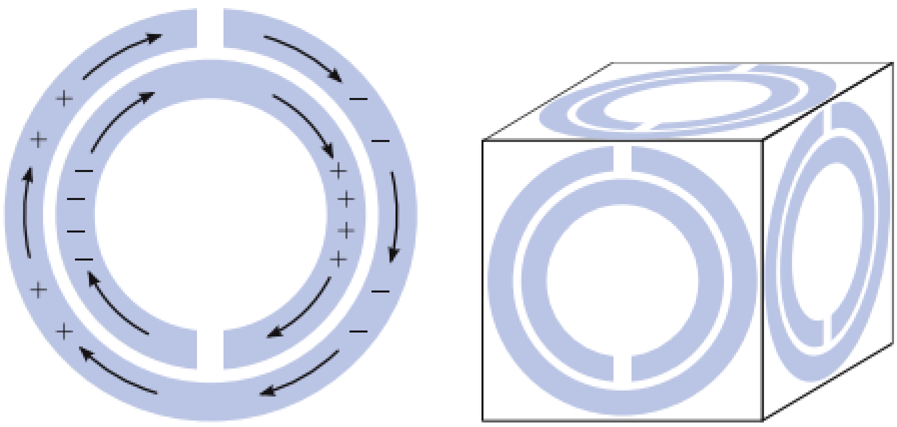

Figure 2.5: Left: Split-ring resonator (SRR) showing induced currents due to a perpendicular magnetic field.

Right: Arrangement of SRRs in a 3D lattice to form an isotropic metamaterial.[11]

- Metamaterials offer an ideal platform for studying emerging new physical phenomena and hold promising prospects for future applications. As an effective medium, several terahertz-absorbing metamaterials have been proposed in recent years. These high-performance absorbers are typically fabricated using periodic matrix structures based on various resonant architectures. These structures can efficiently confine and absorb incident electromagnetic fields, achieving high absorption across multiple bands. However, most metamaterials suffer from limitations in their practical applications, such as a fixed operating frequency range and a specific absorption level. These materials rely on specific geometries for their basic cellular structure. Dynamic control methods, urgently needed for these materials, still require rapid solutions, as these devices cannot be modified [11]

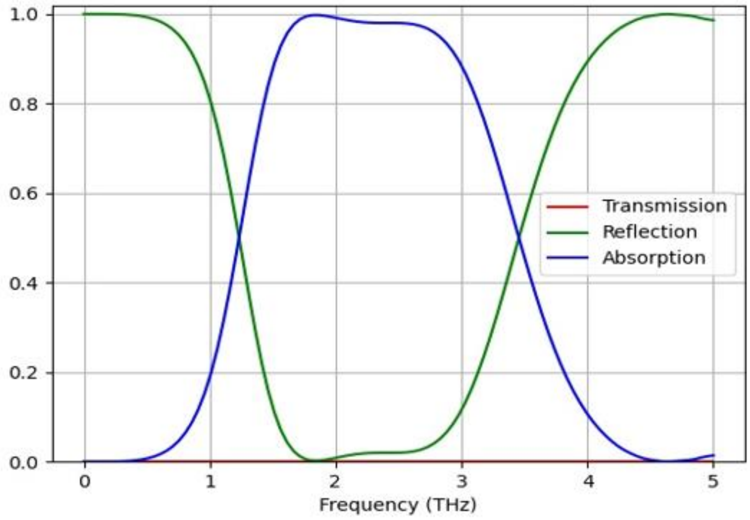

Figure 2.6: Frequency Response of a Metamaterial Absorber (Absorption, Reflection, and Transmission vs Frequency)

4) Applications

- Cloaking and Stealth Technology

Military applications involve concealing aircraft, ships, and vehicles to evade detection and enemy radar. [9]

- Miniaturized Medical Devices

Metamaterials are used in the manufacture and development of miniaturized medical devices, such as precision surgical instruments, drug delivery systems, and laboratory diagnostic devices on a chip. [9]

- **Sensors and Detection**

These materials are used to develop highly sensitive sensors for detecting chemicals, biological agents, and hazardous materials in security, airport security, environmental monitoring, and healthcare. [9]

- **Telecommunications**

Improving radio-wave processing leads to better reception, increased bandwidth, faster data transmission, and enhanced security in communications, benefiting mobile phones, satellite communications, and wireless networks. [9]

- **Clean Energy**

Metamaterials improve the efficiency of solar cells, making solar energy more practical and accessible. These materials are also used in photovoltaic solar thermal systems and energy harvesting technologies. [9]

- **Advanced displays**

Metamaterials are used in the manufacture of high-quality displays, including 3D displays and augmented reality and virtual reality applications. [9]

- **Absorption**

Metamaterials with the frequency range required for electrical or magnetic resonance are fabricated using a basic cellular structure. The incident electromagnetic wave enters the Metamaterials, where it is absorbed and remains there due to the lack of reflection [9]

3. Metasurfaces :

1) Definition: Metasurfaces are considered a dual analog of ultra-fine materials and play a crucial role in controlling electromagnetic wave properties such as phase, amplitude, and polarization. Their advantages lie in low loss, ease of fabrication due to their two-dimensional nature compared to metamaterials, and the ability to alter the wavefront and control polarization through engineering. They also possess exceptional thinness, allowing engineers to study their electromagnetic response for specific applications through high design flexibility, which can lead to technological breakthroughs in numerous fields. Furthermore, these materials enable us to calculate the transmission and reflection coefficients using standard transmission-line relationships .These materials allow us to calculate the transmission and reflection coefficients using standard transmission line relationships: [2]

$$s_{11} = \frac{AZ_0+B-CZ_0^2-DZ_0}{AZ_0+B+CZ_0^2+DZ_0} \tag{3}$$

$$S_{21} = \frac{2Z_0}{AZ_0 + B + CZ_0^2 + DZ_0} \tag{4}$$

2) Structure and Working Principle

Metasurfaces are considered two-dimensional analogs of metamaterials due to their ease of fabrication and two-dimensional properties. In contrast, Metasurfaces consist of periodic or quasi-periodic arrangements of subwavelength elements known as unit cells. Each unit cells acts as a single scatterer that interacts with the incident electromagnetic wave. By engineering these unit cells, Metasurfaces can induce abrupt changes in phase, amplitude, or polarization at the interface.

This surface control enables Metasurfaces to efficiently manipulate wave propagation without requiring three-dimensional structures. [12] [6]

- **Electromagnetic Control**

In recent years, metasurfaces modeling has been considered an important technique in electromagnetic wave engineering, including wavefront shaping. Due to these numerous electromagnetic properties, Metasurfaces have garnered significant attention from the scientific research community. [13]

- **Phase control**: Metasurfaces can modify the amplitude and induce a sudden phase shift in the incident wave within the subwavelength range through the interaction of light with matter, thereby achieving more efficient wavefront modulation. [13]
- **Amplitude control:** This allows for adjusting the intensity of transmitted or reflected waves, enabling energy redistribution and filtering applications. [13]
- **Polarization control:** Metasurfaces can transform or control polarization states, such as transforming from linear polarization to circular polarization. [13]

3) Applications: Metasurfaces are distinguished by several features that have made them increasingly popular, particularly their ability to control electromagnetic waves, such as phase, amplitude, and polarization. This has led to their emergence as a modern technology used in many leading applications in our field, [7] including:

- **Polarization shift:** This refers to the direction of vibration of the electric field, allowing us to change the polarization after reflection and transmission. This is achieved by controlling the wavelength difference between two perpendicular components. This technique aims for a strong polarization shift and a reduction in the original polarization. [7]

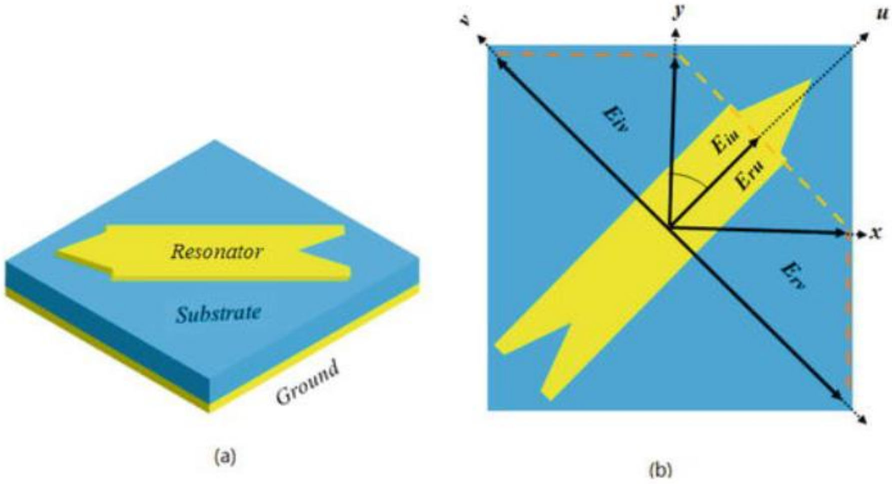

Figure 2.7: Meta surface Configuration (Resonator–Substrate–Ground) and Electromagnetic Wave Interaction Mechanism [7]

- **Radar cross-section reduction:** This refers to the detectability of an object by radar using Metasurfaces cells with a mirror and a 180° phase difference. [7]

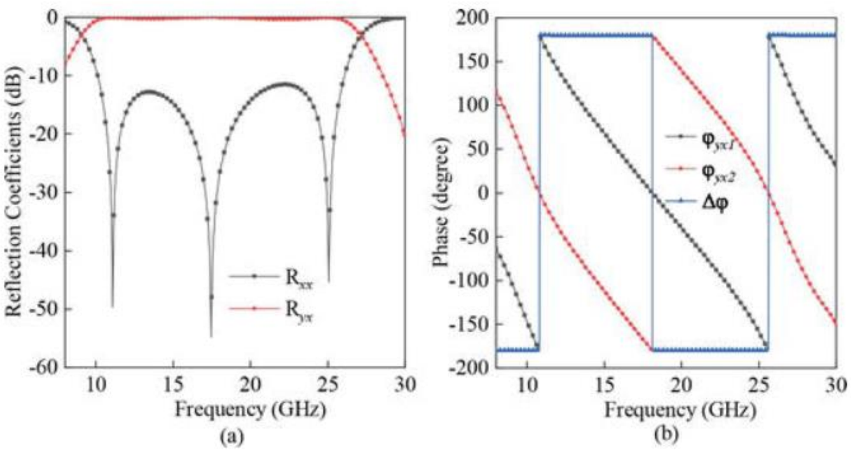

Figure 2.8: Analysis of Reflection Coefficients and Phase Difference in the Metamaterial System [7]

- **Metasurfaces absorber:** This technology uses a metal-insulator-ground metal structure to absorb electromagnetic waves. It operates in both narrow and wide bands and aims to reduce the reflection rate and increase the absorption rate. [7]

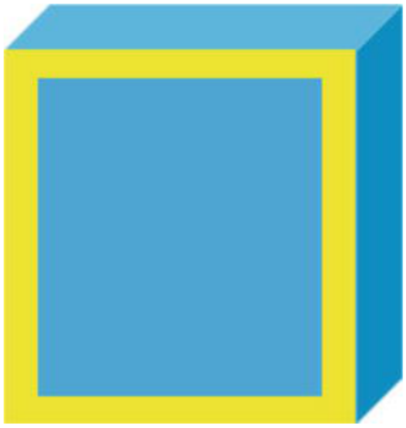

Figure 2.9: Schematic Representation of a Multilayer Metamaterial Structure [7]

4.The relationship between metamaterials and metasurfaces:

Metasurfaces represent a two-dimensional extension of metamaterials and complement them in purpose by controlling electromagnetic waves. The difference between them lies in the type of control: Metasurfaces s are characterized by surface control, while metamaterials are characterized by internal control. [12]

Item	**Metamaterials**	**Metasurfaces**	**Relation**
Definition	Metamaterials are structures and properties not found in nature, and are highly valued for their unique electromagnetic properties	Metasurfaces are considered a dual analog of ultra-fine materials and play a crucial role in controlling electromagnetic wave properties	Metasurfaces are a two-dimensional extension of Metamaterials
Dimensions	Three-dimensional (3D)	Two-dimensional (2D)	A structural shift from volumetric (three-dimensional) structures to planar

			(two-dimensional) configurations
Structure	It consists of periodically distributed meta-atoms	It consists of surface elements (unit cells) arranged on a periodic surface	The same structural principle, but on a smaller scale
Control method	Controlling wave propagation within the medium (complete control)	Surface control	Different method
manufacturing	Relatively complex	Easier to manufacture	Metasurfaces technology provides a practical solution for Metamaterials applications
Wave control	Controls the electrical permittivity (ε) and magnetic permeability (μ) within the material	Controls the phase, amplitude, and polarization at the surface	Integrates with electromagnetic control
Size	relatively large	ultra-thin	Reduced size while maintaining functionality

Table 2.1: Comparative Analysis of Metasurfaces and Metamaterials: Definitions, Dimensions, Structure, and Electromagnetic Properties

- Metasurfaces achieve similar or enhanced functionality by controlling wave properties at the interface level, resulting in reduced waste, simplified manufacturing processes, and increased integration capabilities. Therefore, the relationship between them is complementary. [12]

5. Electromagnetic absorber :

Terahertz waves in the excitation spectrum span both the microwave and infrared ranges, covering frequencies from 0.1 to 10 THz (Rahm et al., 2013). Terahertz waves possess significant technological value, enabling the transmission of crucial physical information and opening up numerous and diverse applications in wireless communications, imaging, spectroscopy, and other fields. This information requires the use of modulators, absorbers, and filters to process the terahertz waves. [3]

1) Definition: In the field of electromagnetic materials, absorption is defined as a material's ability to dissipate the energy of an incident wave and convert it into another form of energy. It is expressed by the equation

$$A = 1 - R - T \qquad (5)$$

where R represents reflection, and T represents transmission. This equation is derived from the principle of conservation of energy. In practice, part of an incident electromagnetic wave is reflected from a surface, another part is transmitted through the material, and the remainder is absorbed. For an ideal absorber, both reflection and transmission are at their lowest levels ($R \approx 0$ and $T \approx 0$), resulting in near-total absorption ($A \approx 1$). This condition is met by designing the absorber structure to match the impedance of free space and suppress transmission using a metallic ground layer. [3]

2) Types of absorbers:

In recent years, electromagnetic wave absorption technology has emerged as a leading research field,

demonstrating enormous potential for applications in diverse areas, including energy conversion, environmental monitoring, and more. Devices with broadband electromagnetic wave absorption properties are widely used in communications, military applications, medical diagnostics, and medical imaging. Thanks to the depth of fundamental research and the feasibility of manufacturing this technology, related research has led to the development of new types of devices. Graphene and vanadium are among the most important materials for electromagnetic wave absorption, particularly in the terahertz frequency range, owing to their ability to control absorption. [5]

1) Conventional electromagnetic absorbers :

- **Resonant Absorbers**: These are engineering designs that aim to reduce the reflection of incident waves and absorb energy within the material, such as the Salisbury screen and the Jaumann absorber. For example, the Salisbury screen's basic structure consists of three layers: an upper resistive plate that receives the electromagnetic wave and converts its energy into heat; a lower plate, called the metallic coating plate, that prevents the wave from passing through; and the most important middle layer, the insulating layer, which determines the phase of the wave by 180 degrees, allowing the waves to return a distance of λ/4. [5]

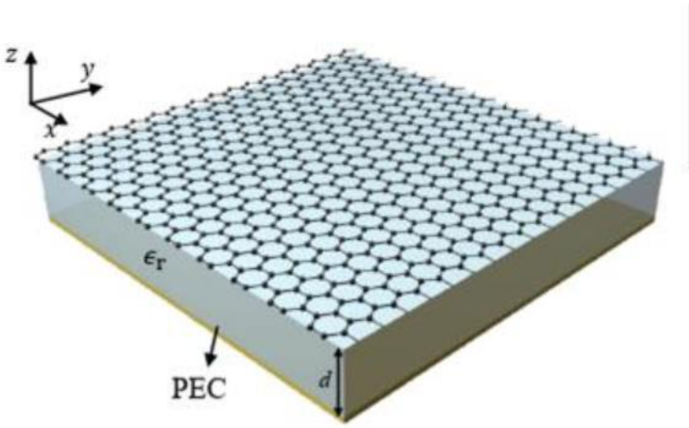

Figure 2.10: Metasurfaces Structure with Dielectric Substrate and PEC Ground [7]

- **Broadband Absorbers:** This type aims to gradually transfer energy from the external medium to the internal medium. An example of this is the geometrically transitioned absorber. This method allows us to reduce reflectivity. A second type, called the low-density absorber, is also available. Using this layer, we can generate low loss and high absorption. The Jaumann absorber extends the Salisbury design by incorporating multiple resistive layers, thereby improving bandwidth. [5]

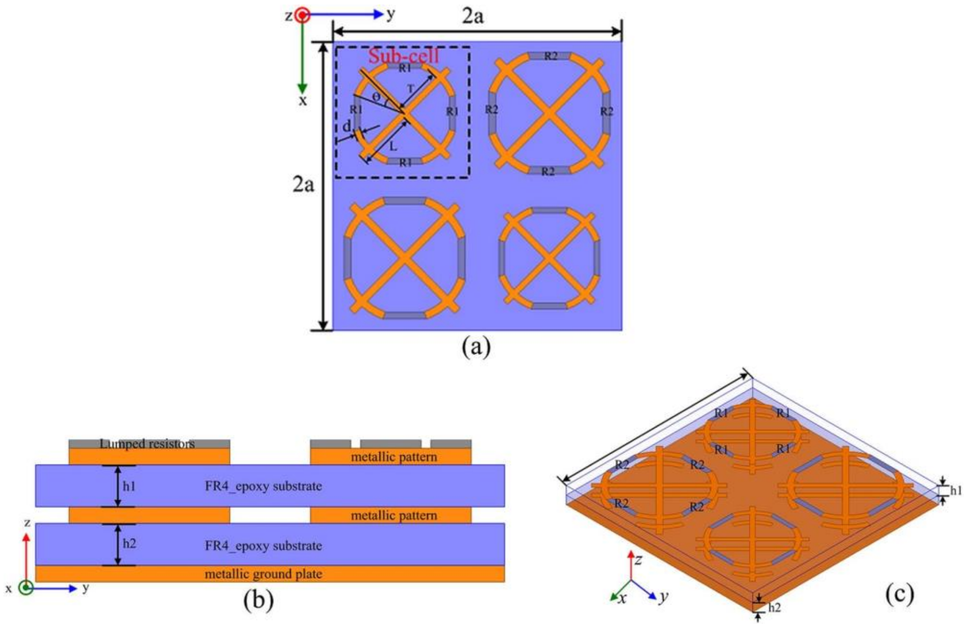

Figure 2.11: Multilayer Metamaterial Absorber Structure [7]

2) Metamaterials absorber :

1) Definition :

An MMA is a type of metamaterial that is specifically designed to absorb incoming EM radiation over a broad range of frequencies or at selected frequency bands. The absorbers are characterized by their ability to convert incident EM energy into heat, thus preventing the reflection or transmission of the waves. By controlling the geometry and material properties, MMAs can achieve near-perfect absorption across microwave, terahertz, and optical ranges (Electromagnetic Properties of Metamaterial Absorbers and Applications) [5]

2) Structures :

Metamaterial absorbers (MMAs) are metamaterials specifically designed to absorb incident electromagnetic radiation across a wide range of frequencies or within specific frequency bands. These materials are characterized by their ability to convert incident electromagnetic energy into heat, thus preventing the reflection or transmission of waves. By controlling the geometry and properties of the materials, metamaterial absorbers can achieve near-perfect absorption ($A \approx 1$) across microwave, ultrasonic, and light frequency ranges (see: Electromagnetic Properties of Metamaterial Absorbers and Their Applications). The absorption mechanism relies on free-space impedance matching and resonant effects. [6]

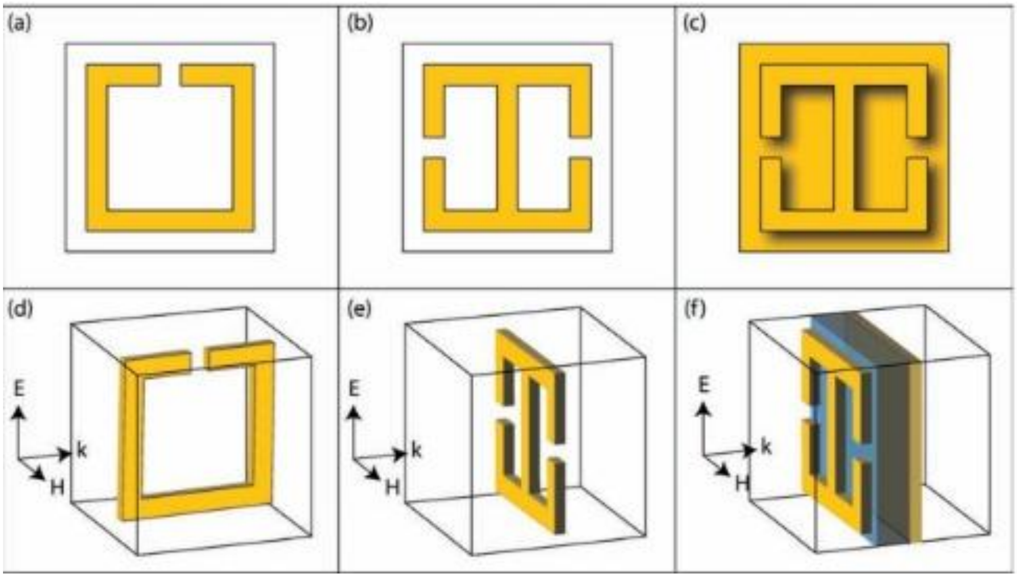

Figure 2.13: Schematic diagram of the two basic cells of the metamaterial used to produce a magnetic and electrical response [3]

3) Types of metamaterial absorber :

Metamaterial absorbers operate on the fundamental principle of controlling electromagnetic wave interactions. Unlike conventional absorbers, metamaterial absorbers are designed with core cells that exhibit specific responses at particular electromagnetic frequencies. [14]

These core cells typically consist of metallic resonators that interact with both the electrical and magnetic components of the incident electromagnetic waves. Through precise design of their geometry and selection of appropriate core-cell materials, metamaterial absorbers can achieve near-perfect absorption, ensuring minimal reflection and zero penetration of the incident wave. Electromagnetic wave absorbers are generally classified as narrowband or broadband, each designed for specific applications. The second type has a permittivity less than zero and a permeability greater than zero. This type is called an epsilon-negative (ENG), in which, in certain frequency ranges, it exhibits properties similar to those of natural materials such as plasma, doped semiconductors, and others: [14]

- Narrowband absorbers will be used to reduce the specific absorption rate (SAR) in 5G devices, enhancing user safety by absorbing excess electromagnetic energy. Another design, developed for Wi-Fi applications, provides effective protection against interference at 2.4 GHz and 5 GHz frequencies. [14]

- Broadband absorbers are designed to operate across wider frequency bands, making them suitable for advanced applications such as stealth technology, radar systems, and multi-band wireless communications. These absorbers utilize multi-resonant structures, integrated resistors, or low-loss dielectric materials. [14]

- A three-band multi-band absorber array, designed for terahertz sensing applications, demonstrated high quality factor values and high sensitivity for gas detection by refractive index variation, achieving a peak SAR of approximately 99.9%. It also exhibited excellent quality factors and polarization independence, making it a strong choice for environmental and biochemical sensing. [14]

- Tunable absorber designed to achieve tunable absorption through the synergistic interaction of its components. The graphene layer plays a crucial role in enhancing absorption due to its tunable conductivity and strong interaction with terahertz waves. This is because the surface plasmon resonance of graphene and its ability to confine electric fields are essential for achieving high absorption at specific frequencies. The absence of graphene disrupts this resonance, reducing absorption efficiency. The vanadium dioxide (VO2) layer contributes to the absorber's tunability and switchability due to its phase-transformation properties (from an insulating to a metallic state). The absence of VO2 results in the absorber losing its ability to dynamically modulate its absorption characteristics and match the structure's impedance, leading to a mismatch between the metamaterial and free space, thereby reducing absorption across the spectrum. [14]

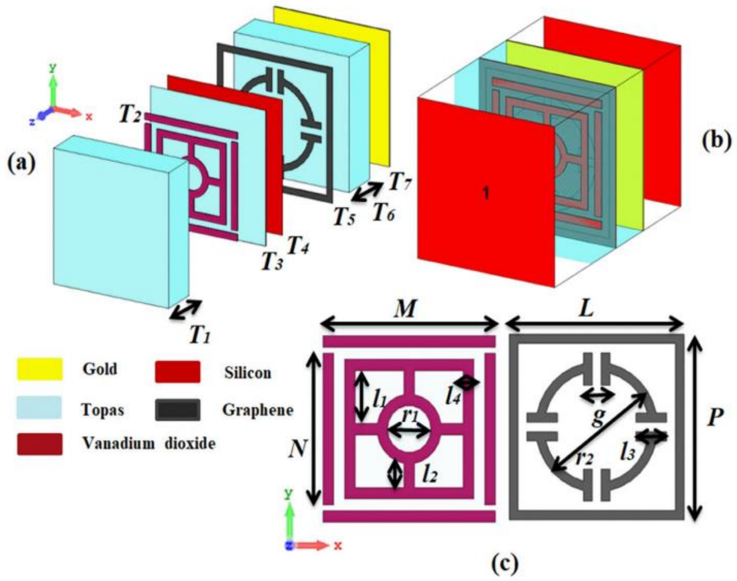

Figure 2.14: A three-dimensional perspective of the proposed metamaterial structure, showing the seven layers from multiple angles and a front view of the vanadium dioxide (VO2) layer and the graphene layer, highlighting their configurations within the structure.[14]

4) Graphene :

Graphene is a two-dimensional material consisting of an extremely thin layer of carbon atoms, no more than one atom thick, arranged in a hexagonal honeycomb structure and linked by sp^2 bonds. It is not an integral part of the carbon itself, but rather suspended or freely attached to an external surface. Graphene is one of the thinnest and strongest known materials and possesses exceptional electrical properties. Among these properties are: [16]

- Graphene is an excellent conductor of electricity and heat, as its electrons behave as massless particles and move at extremely high speeds. This is due to its regular hexagonal crystal structure; thanks to this unique structure, scattering processes disappear, resulting in extremely high electrical conductivity, high electron mobility, and extremely high thermal conductivity. [16]
- Graphene consists of a single, thin layer of atoms (about 0.34 nanometers), yet it possesses incredible strength—stronger than steel relative to its weight—and unlike steel, it can be bent or stretched without breaking. It is also extremely flexible and lightweight, and is used in flexible electronics and nanosurfaces. [16]
- Graphene reacts strongly to electromagnetic waves due to free electrons and surface plasmon phenomena. It exhibits strong and controllable absorption in the terahertz (THz) frequency range and can be used in absorbers, detectors, and rectifiers. [16]
- One of the most important properties of graphene is its electronic controllability, which allows its properties to be changed by applying an electrical voltage that controls the conductivity, absorption, and resonant frequency. [16]

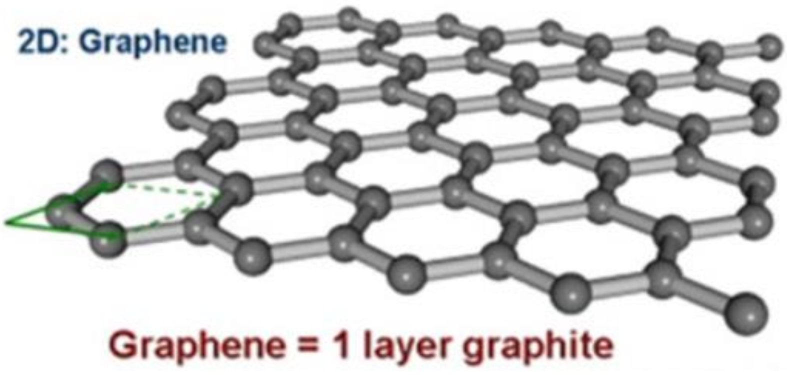

Figure 2.15: Graphene, the optimal form of graphite, is used as a basic two-dimensional building material for carbon structures of all dimensions.[1]

5) Vanadium :

Vanadium is a chemical element in the transition metal series, with the symbol V and atomic number 23. Its importance lies in its compounds, particularly vanadium dioxide (VO_2), which exhibits unique and reversible phase transitions from a metallic to an insulating state. VO_2 undergoes a structural phase transition and is used in engineering and advanced applications. [15]

- Properties of Vanadium

The VO_2 film can modulate the terahertz wavefront, thereby adjusting the transmittance, absorption, and reflection of terahertz waves under the influence of phase-change temperature. In its insulating state, VO_2 is almost completely transparent to terahertz waves. This is because the performance of VO_2 films during ultrafast phase transitions closely matches the terahertz-wave resonant properties of metamaterials. Controlling the interaction between terahertz radiation and metamaterials enables modulation of the materials' output response. [15]

- Vanadium dioxide (VO2) undergoes a phase transition to a rutile-type tetrahedral structure with a variable energy gap and conductivity upon reaching the phase transition point. This structure exhibits metallic properties, including strong absorption and reflection of low-frequency infrared radiation, while its transmittance to visible light remains nearly constant. Studies have shown that the thermal conductivity of vanadium dioxide in its metallic phases at high temperatures is significantly higher than that of vanadium dioxide at room temperature. The thermal conductivity of vanadium dioxide can be high, and the phase transition is characterized by rapid, stable, and reflective behavior.

The phase transition temperature varies between heating and cooling processes, leading to magnetic hysteresis. [15]

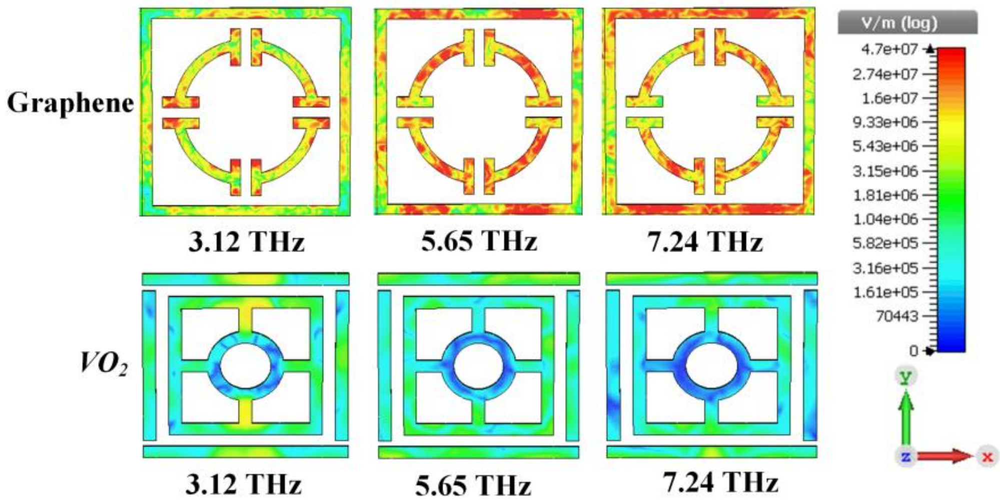

Figure 2.16: Electric field distributions of the multiband absorber, for both graphene and VO2, respectively, in the terahertz frequency range.[14]

6. Conclusion

In conclusion, this chapter has identified metamaterials and Metasurfaces as key innovations in various fields, including electromagnetic wave engineering. They are distinguished by their ability to control wave propagation in ways not found in nature, thanks to their microscopic structure, with dimensions smaller than the wavelength.

- The chapter also discussed the role of Metasurfaces as a dual extension of metamaterials, offering numerous advantages such as ease of manufacturing and control over wave properties, making them effective solutions in many applications.

- Electromagnetic absorbers, their types, and metamaterial-based properties were also addressed. These absorbers enable us to achieve near-complete absorption, opening up a wide range of applications.

- Metamaterials, Metasurfaces, and electromagnetic absorbers are among the leading fields in scientific research and future applications, such as communications, energy, and defense, making them a focus of increasing research.

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Chapter III : Results and discussion

1. Introduction

This chapter presents the simulation results of a terahertz metamaterial absorber incorporating graphene as the active material. The objective is to evaluate the electromagnetic response of the proposed structure and demonstrate its capability to achieve high, broadband absorption in the terahertz frequency range. Graphene, owing to its tunable surface conductivity and unique plasmonic properties, plays a crucial role in enhancing absorption performance and enabling dynamic control. The analysis is carried out using full-wave electromagnetic simulations, in which key parameters, such as geometric dimensions and material properties, are systematically investigated. The absorption characteristics are examined in terms of frequency response, bandwidth, and peak efficiency. In addition, the influence of the graphene layer and its optimization are discussed to highlight the underlying physical mechanisms responsible for the observed behavior. The results presented in this chapter provide insight into the design of efficient terahertz absorbers and establish a foundation for further optimization and practical implementation.

2. Graphene properties

Graphene is a two-dimensional material composed of a single layer of carbon atoms arranged in a hexagonal lattice. Its exceptional electrical and optical properties make it particularly suitable for terahertz applications, especially in metamaterial absorbers where tunability and strong light–matter interaction are required.

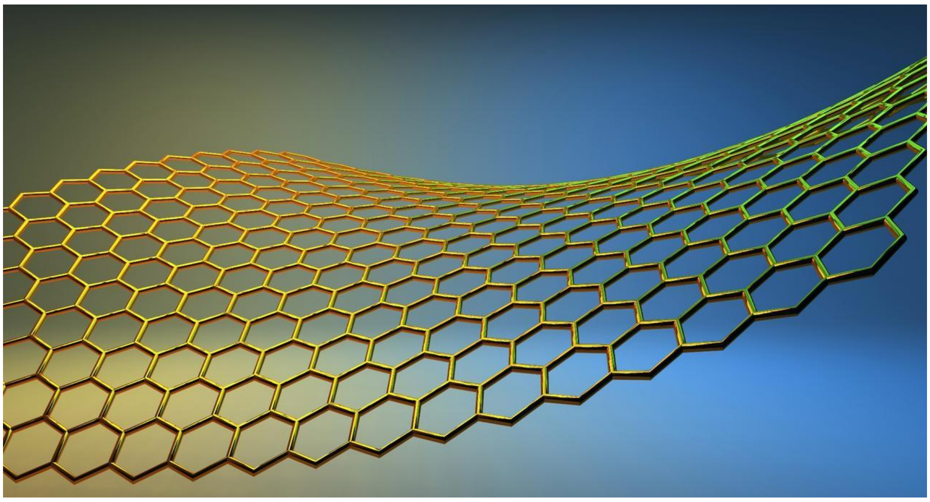

Figure 3.1: 2D layer of graphene.

The electromagnetic behavior of graphene is commonly described through its surface conductivity, which can be modeled using the Kubo formalism, which accounts for both **intraband** and **interband** electronic transitions. The total surface conductivity is expressed as

$$\sigma(\omega) = \sigma_{\text{intra}}(\omega) + \sigma_{\text{inter}}(\omega) \quad (1)$$

The intraband (Drude-like) contribution is:

$$\sigma_{\text{intra}}(\omega) = \frac{2ie^2k_BT}{\pi\hbar^2(\omega+i/\tau)} \ln\left[2cosh\left(\frac{E_F}{2k_BT}\right)\right] \quad (2)$$

The interband contribution is:

$$\sigma_{\text{inter}}(\omega) = \frac{e^2}{4\hbar}\left[\frac{1}{2} + \frac{1}{\pi}\arctan\left(\frac{\hbar\omega-2E_F}{2k_BT}\right) - \frac{i}{2\pi}\ln\frac{(\hbar\omega+2E_F)^2}{(\hbar\omega-2E_F)^2+(2k_BT)^2}\right] \quad (3)$$

Where :

- e is the electron charge
- $\hbar$ is the reduced Planck constant
- k_B is the Boltzmann constant
- T is the temperature
- E_F is the Fermi energy (chemical potential)
- ω is the angular frequency
- τ is the carrier relaxation time

Figure 3.2 depicts the variation in graphene conductivity with frequency for different chemical potential values. In the terahertz frequency range ($\hbar\omega \ll E_F$), the intraband contribution dominates, and the conductivity can be approximated as:

$$\sigma(\omega) = \frac{e^2E_F}{\pi\hbar^2}\frac{1}{\Gamma-i\omega} \quad (3)$$

This expression highlights the tunability of graphene through the Fermi level E_F, which can be controlled via electrostatic gating or chemical doping. Increasing E_F generally enhances conductivity and shifts the absorption response. This behavior shall be clearly observed in simulation results.

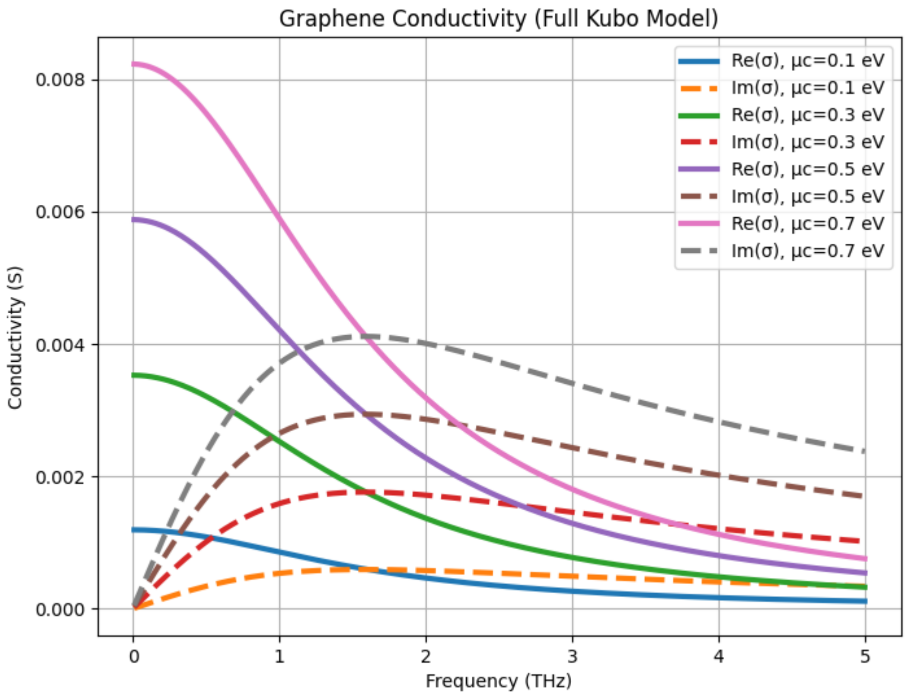

Figure 3.2: Variation of the complex conductivity of the graphene for different values the frequency.

3. **Graphene based metamaterial absorber**

A typical metamaterial absorber consists of unit cells of three-layer configuration designed to achieve near-perfect absorption of incident electromagnetic waves. The structure includes a continuous metallic ground plane at the bottom (thickness 500 nm), which blocks transmission; a dielectric spacer (refractive index 1.53 and thickness 21 µm) in the middle that controls electromagnetic coupling; and a patterned graphene layer on top that acts as a tunable resonator. The unit cell period is set to be 40 µm. When the structure is irradiated from the top, the incident wave interacts with the graphene layer, inducing localized surface plasmons and resonance effects. By carefully selecting the geometry and material properties, the impedance of the structure can be matched to free space, minimizing reflection while the metallic backing suppresses transmission, resulting in strong absorption within the targeted frequency range, particularly in the terahertz regime. Figure 3.3 gives a 3D view of the simulation and the structure.

The finite-difference time-domain (FDTD) method is widely used to compute the absorption characteristics of metamaterial absorbers by numerically solving Maxwell's equations in the time domain. In this approach, the simulation region is discretized into a spatial grid, and the electromagnetic fields are updated iteratively over time as an incident wave propagates through the structure. By placing appropriate monitors, the reflected and transmitted power spectra are calclated and determined using $A(\omega) = 1 - R(\omega) - T(\omega)$ For structures with a metallic ground plane, transmission is effectively zero, so absorption can be directly obtained from the reflection. The FDTD method is particularly advantageous for broadband analysis and complex geometries, making it well suited for studying terahertz metamaterial absorbers.

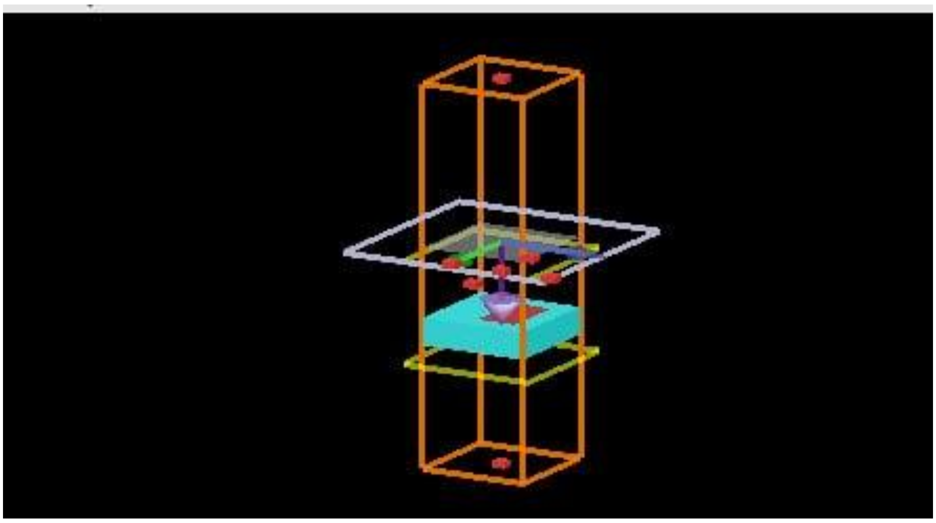

Figure 3.3: The proposed absorber 3D cross-sectional view and the simulation region.

The initial FDTD simulation provides the spectral response of the structure in terms of reflection, transmission, and absorption. The results show that transmission is effectively negligible due to the presence of the metallic ground plane, while reflection is significantly minimized over a specific frequency range. Consequently, the absorption approaches unity, indicating near-perfect energy dissipation within the structure. In particular, a strong absorption band is observed in the 2–3 THz region, where the absorber performs optimally, confirming the effectiveness of the designed geometry and material configuration. Figure 3.4 gives the transmission, reflection, and absorption of the structure for a frequency band spanning the region from 0 to 5 THz.

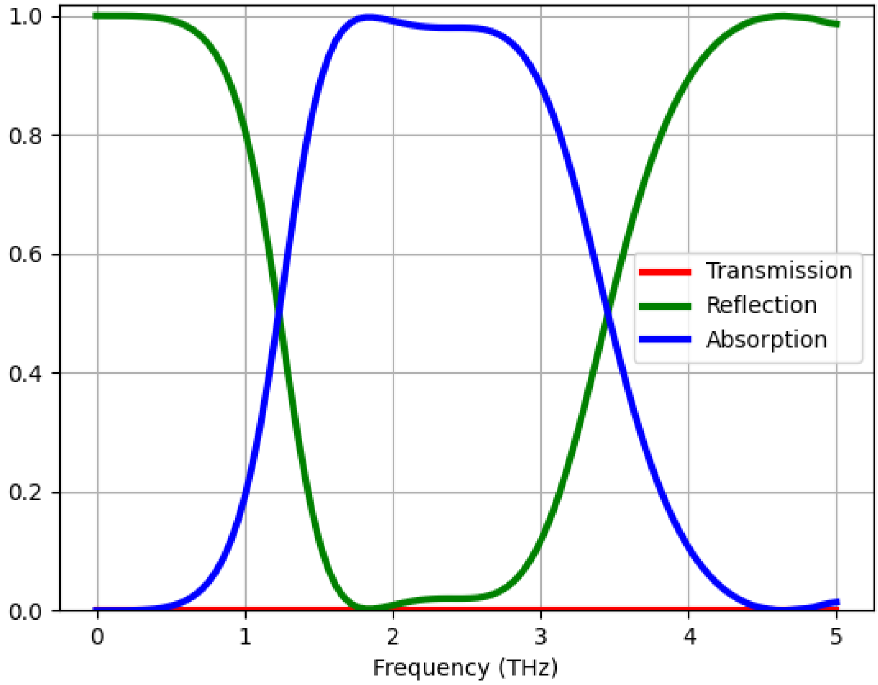

Figure 3.4: Transmission, reflection, and absorption of the proposed metamaterial absorber.

Furthermore, we have conducted additional simulations using transmission line theory. The simulated effective impedance of the absorber clearly explains the observed near-perfect absorption behavior. In the frequency range where absorption approaches unity, the real part of the normalized impedance converges to approximately 1, indicating excellent impedance matching to free space, while the imaginary part approaches 0, reflecting minimal reactive (stored) energy within the structure. This combination suppresses reflection at the interface and allows the incident electromagnetic wave to fully enter and dissipate within the absorber, confirming that optimal absorption occurs when the impedance is both real-valued and closely matched to that of free space. Results are depicted in Figure 3.4.

3.1 Effect of graphene chemical potential

The effect of varying the graphene chemical potential on the absorber performances has been investigated. Figure 3.5 depicts the absorption spectra for chemical potentials of 0, 0.1, 0.2, 0.3, and 0.4 V, respectively.

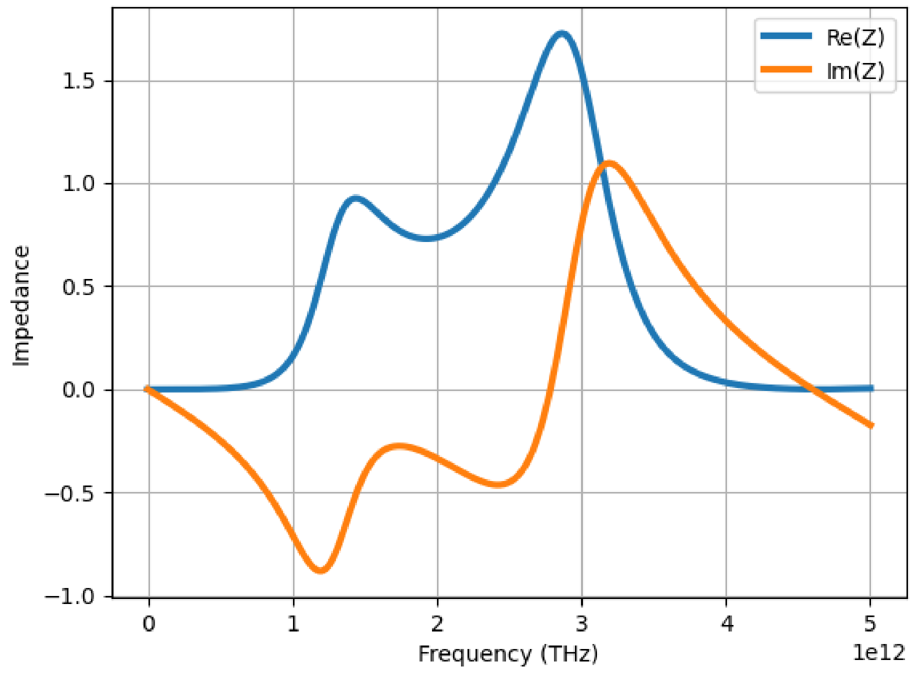

Figure 3.5: Complex effective impedance of the proposed metamaterial absorber.

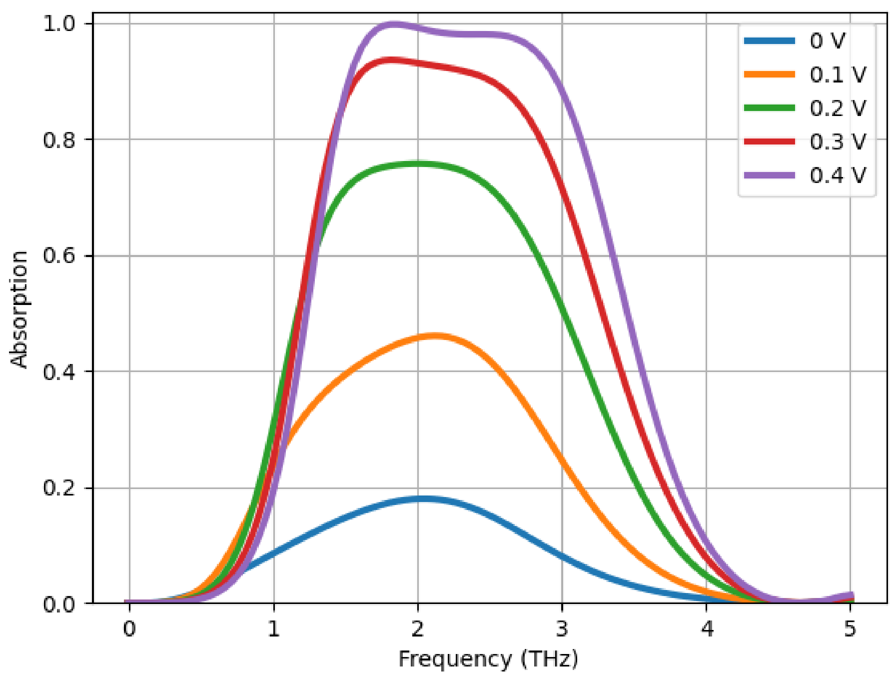

Figure 3.6: Absorption spectra for different values of the graphene chemical potential.

The simulation results reveal a strong dependence of the absorber performance on the graphene chemical potential, highlighting its role as an active tuning parameter. As the chemical potential increases, the surface conductivity of graphene, typically described by the Kubo Model, is significantly modified, leading to a noticeable shift in the absorption spectrum. In particular, higher chemical potentials tend to enhance the interaction between the incident terahertz wave and the graphene layer, resulting in stronger confinement of electromagnetic energy and, consequently, improved absorption. This is often accompanied by a spectral shift in the resonance frequency, which can shift toward higher frequencies due to increased carrier concentration. Conversely, at lower chemical potentials, the absorption peak becomes weaker and less defined, reflecting reduced tunability and weaker plasmonic response. These results demonstrate that by electrically controlling the graphene chemical potential, the absorber can be dynamically tuned in both amplitude and spectral position, making it highly suitable for reconfigurable terahertz applications.

3.2 Effect of graphene layer width

The influence of the graphene layer size was investigated by varying its lateral dimension from 16 to 28 µm and analyzing the corresponding absorption spectra (Figure 3.7).

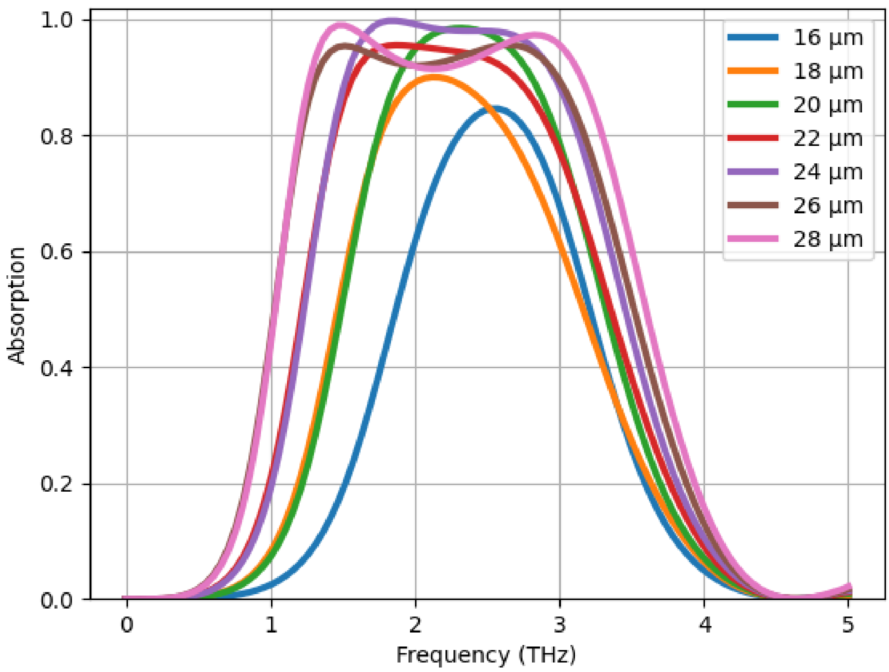

Figure 3.7: Absorption spectra for different values of the graphene layer width.

The results reveal that the graphene geometry plays a crucial role in tuning both the resonance position and the absorption magnitude. As the size increases, the effective interaction area between the incident terahertz wave and the graphene layer increases, leading to stronger coupling and a noticeable redshift of the absorption peak toward lower frequencies. Additionally, the absorption bandwidth tends to broaden for intermediate dimensions, indicating improved impedance matching over a wider spectral range. However, beyond a certain size, the enhancement saturates, and a slight degradation in peak absorption may occur due to increased losses and mismatch effects. These observations highlight that an optimal graphene dimension exists within the studied range, where near-unity absorption and broadband performance are simultaneously achieved.

3.3 Effect of spacer dielectric material

The effect of various spacer dielectric materials on device performance has been analyzed, and the evolution of absorbance versus frequency for AL2O3, Fe2O3, Si3N4, SiO2, HfO2, and TOPAS is shown in Figure 3.8.

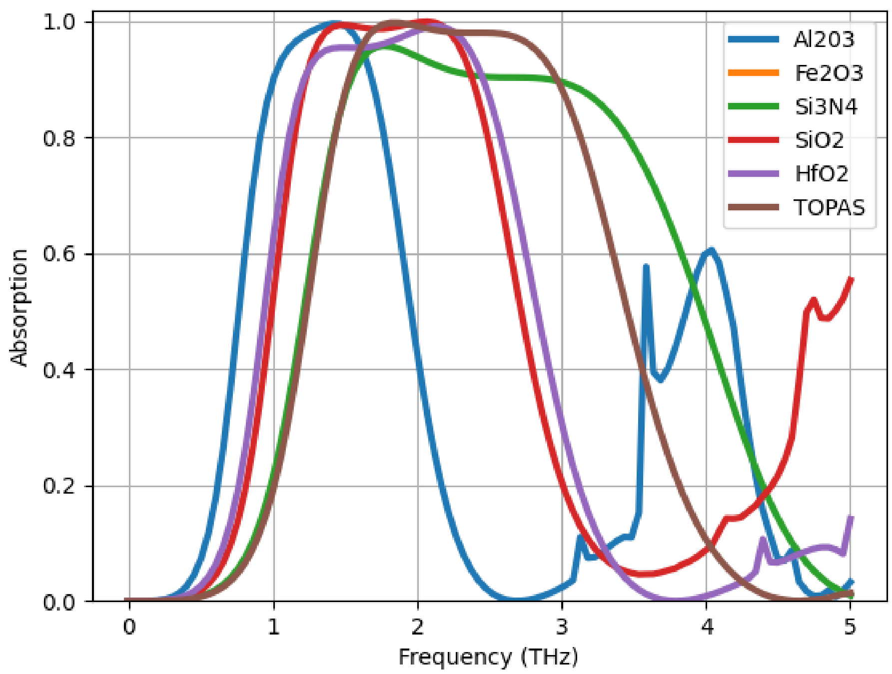

Figure 3.8: Absorption spectra for different materials of the spacer.

Materials such as Al_2O_3, Fe_2O_3, Si_3N_4, SiO_2, HfO_2, and TOPAS exhibit distinct dielectric constants and loss tangents, which directly affect impedance matching and resonance conditions. As a result, the absorbance profiles show noticeable variations in both peak intensity and bandwidth across the frequency range. High-permittivity materials like HfO_2 and Fe_2O_3 tend to shift the resonance toward lower frequencies and can enhance absorption strength, while low-permittivity materials such as Si_3N_4 and TOPAS generally lead to broader but slightly weaker absorption. This demonstrates that careful selection of the spacer material is crucial for tuning the absorber's spectral response and optimizing its overall performance.

3.4 Effect of graphene layer shape

We consider a spacer made of Si_3N_4 because it exhibits the widest absorption spectrum. The influence of increasing the number of vertices in the top graphene layer on absorption has been investigated, as shown in Figure 3.9.

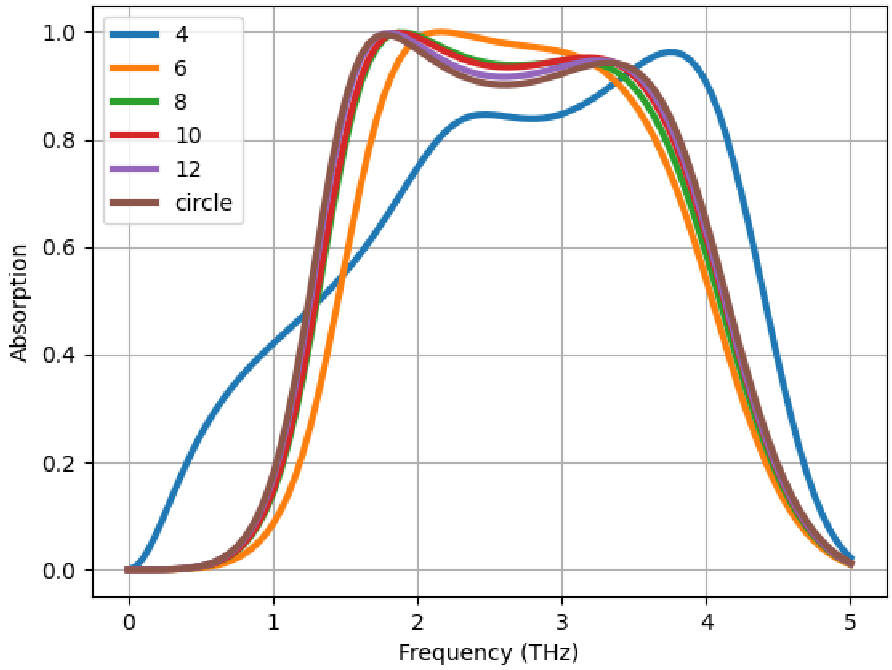

Figure 3.9: Absorption spectra for different numbers of vertices of the top graphene layer 2D shape.

The impact of increasing the number of vertices in the graphene layer shape on absorber performance has been systematically analyzed, revealing a clear enhancement in absorption with increasing geometric complexity. As the number of vertices increases, the graphene pattern more closely approximates a curved or circular geometry, thereby improving the uniformity of the induced surface currents and strengthening the light–matter interaction at the nanoscale. This smoother current distribution reduces scattering losses and enhances impedance matching with free space, leading to stronger confinement of electromagnetic energy within the structure. Consequently, the absorbance increases nearly proportionally with the number of vertices, indicating a direct relationship between geometric refinement and absorption efficiency. This trend highlights the importance of precise geometrical control in graphene-based metamaterial absorbers, where even incremental changes in shape discretization can significantly influence the overall optical response.

3.5 Effect of spacer thickness

We study a spacer made of silicon nitride (Si_3N_4) because it possesses the broadest absorption spectrum. Figure 3.10 illustrates the effect of varying the separator thickness on the electromagnetic absorption characteristics of the superstructure in the terahertz frequency range.

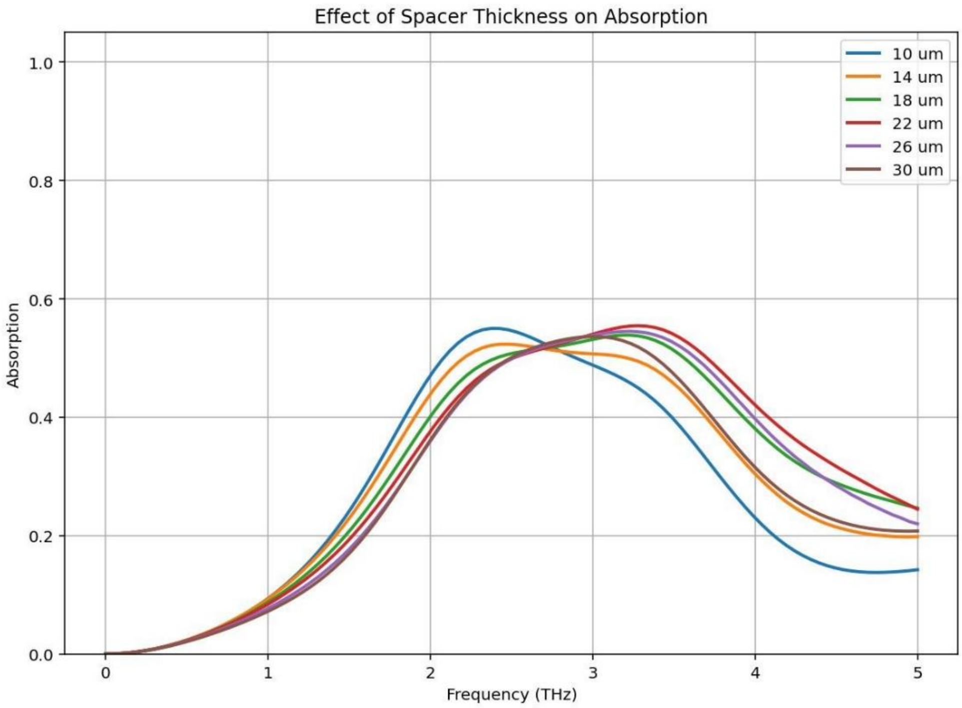

Figure 3.10: Absorption spectra for different spacer thickness

The results show that increasing the separator thickness directly affects the resonant frequency position and the absorption peak value. A gradual shift of the absorption peak towards higher frequencies is observed as thickness increases, indicating a change in the resonant conditions in the structure due to variations in the electromagnetic wave's optical path length in the dielectric layer. Furthermore, absorption values increase and become more stable at the average thickness, demonstrating improved coupling of the incident wave to the resonant structure and reduced reflection. This makes the dielectric thickness a crucial factor in optimizing the absorber's performance and tuning its spectral characteristics for terahertz applications.

4. Conclusion

In this work, a comprehensive numerical investigation of a graphene-based metamaterial absorber was carried out to evaluate its electromagnetic absorption performance in the terahertz regime. The study focused on the influence of key geometric and physical parameters, particularly variations in graphene layer dimensions, on the absorption spectrum. The results demonstrated that tuning the graphene geometry significantly affects both the resonance frequency and the absorption efficiency, confirming its critical role in achieving near-perfect absorption and improving impedance matching conditions. In several configurations, strong absorption peaks were observed, indicating efficient coupling between the incident wave and the designed structure.

General Conclusion

General Conclusion

Modern technology has witnessed significant advancements in wireless communications, electromagnetic sensing, and terahertz applications, leading to a growing need for advanced materials capable of efficiently controlling electromagnetic waves. In this context, metamaterials and metasurfaces have emerged as synthetic materials possessing electromagnetic properties not found in natural materials. These materials allow for innovative control of wave propagation, reflection, transmission, polarization, and absorption, making them a crucial focus in scientific research and modern applications. The terahertz range is currently one of the most important areas of the electromagnetic spectrum, as it lies between the microwave and infrared bands. It possesses unique properties that enable its use in high-speed communication systems, medical imaging, sensors, spectroscopy, and security systems. However, efficiently controlling and absorbing terahertz waves remains a significant challenge due to the limitations of conventional materials. This has led researchers to develop electromagnetic absorbers based on metamaterials and metasurfaces to achieve high absorption and better control of electromagnetic waves. The study of electromagnetic waves is fundamentally based on Maxwell's equations, which describe the relationship between electric and magnetic fields and how waves propagate through different media. Concepts such as reflection, transmission, polarization, and Brewster's angle also contribute to understanding the behavior of waves when interacting with different materials. This understanding is essential for analyzing the performance of electromagnetic absorbers and designing efficient structures to operate within specific frequency ranges. Metamaterial-based absorbers are among the most important modern applications of these materials. They are designed to minimize reflection and transmission, thereby achieving near-complete absorption of the incident electromagnetic energy. These absorbers are characterized by their small size, high efficiency, and ability to operate within narrow or wide ranges. Furthermore, their electromagnetic properties can be controlled by modifying their geometry or the properties of the materials used in recent years, graphene has garnered significant attention in the design of terahertz absorbers due to its unique electrical and optical properties, such as high conductivity and the ability to dynamically control its characteristics by varying the chemical potential. Combining graphene with metasurface structures allows for the creation of tunable and reconfigurable absorbers, increasing absorption efficiency and providing considerable flexibility in various practical applications. To study and analyze these structures in detail, advanced electromagnetic simulation software such as Ansys Lumerical FDTD is used. This software enables the simulation of electromagnetic wave propagation within the designed structures and the analysis of absorption, reflection, and transmission properties under the influence of various geometric and physical parameters. Accordingly, this work aims to design and simulate a metasurface absorber operating in the terahertz range using advanced materials and modern electromagnetic structures, while studying the effect of some engineering factors and material properties on the absorber's performance, in order to reach a high absorption efficiency structure that can be used in modern communications applications, sensors, imaging, and future electromagnetic technologies.