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Numerical investigation of a graphene metamaterial absorber operating in the terahertz domain

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Abstract

In this thesis, we aim to design an absorption device that achieves good results so that the return values are very small, and to achieve this goal there is a need to take advantage of the properties of metamaterials, to reach fundamental results. Graphene they considered one of the most powerful metamaterials due to its distinctive electrical properties and high efficiency. We will simulate an absorber consisting of graphene, control some of the properties of this material until we obtain a good absorption spectrum, and be able to extract the factors affecting the conductivity of graphene, which contribute to Recording almost perfect absorption values.

Keywords: Electromagnetic waves, terahertz spectrum, absorption, metamaterials, reflection, graphene, chemical potential, conductivity, absorption spectrum.

ملخص:

نهدف في هذه المذكرة إلى تصميم جهاز إمتصاص يحقق طيف إمتصاص جيد ،بحيث تكون قيمة الطاقة المنعكسة صغيرة جدا،و من أجل تحقيق هذا الهدف لا بد من الإستفادة من المواد الخارقة للوصول إلى نتائج جوهرية.يعتبر الغرافين المكتشف مؤخرا من أقوى المواد الخارقة و هذا راجع لخصائصه الكهربائية المميزة و كفاءته العالية.سوف نقوم بمحاكاة ماص يتكون من طبقة غرافين ،كما نقوم بالتحكم في بعض الخصائص الخاصة بهذه المادة لكي نحصل على نسبة إمتصاص جيدة و ذلك عن طريق الإستفادة من الناقلية الخاصة بمادة الغرافين التي تساهم في تسجيل طيف إمتصاص شبه مثالي.

الكلمات مفتاحية: الموجات الكهرومغناطيسية، طيف التيراهرتز، الامتصاص، المواد الخارقة، الانعكاس، الجرافين، الجهد الكيميائي، الموصلية، طيف الامتصاص.

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General Introduction

General Introduction

The wave equation, which in turn they considered the basis of electromagnetic theory, was produced based on solving Maxwell’s equations, which represent the four most influential equations in the world. This achievement aims to study the spectrum of electromagnetic waves exactly. The terahertz spectrum. This spectrum they defined by electromagnetic waves in the frequency range between regions. Microwave and infrared radiation, this region is located exactly in the frequency range between 1 and 4 Hz. A spectrum they use in many different areas of research and raises a lot of hope for a range of industrial and other applications. Among these uses, the most important is the absorption mechanism. Absorbers used in the terahertz field transmit electromagnetic waves. Generally, the concept of absorbers is they are multi-layer structures that are bulky and large, but the modern system needs small and compact absorbers. Pipettes are also divided into several types, including pipettes (dielectric, resonant, magnetic), and each type contains advantages and disadvantages. This is what led to the discovery of modern pipettes that aim to obtain a good absorption spectrum in better working conditions, and pipettes that are known for these characteristics are called It is known that metamaterials are artificial materials with distinctive and unique properties. These materials have the ability greatly manipulate the incident electromagnetic wave. This is what makes them different materials compared to natural materials. After the increasing demand for metamaterials because they have fundamental properties, this is what led to the discovery of graphene. The focus of this note was on graphene, which they recently discovered. Carbon they considered a source of this material, or rather, it is a special form of carbon atoms, but it shows strange properties. In addition, promising, capable of making a qualitative leap in the technology space. An absorber consisting of graphene they simulated, with two different designs, namely the uniform design and the fishnet design, and then different results were recorded for the absorption spectrum, but in order to improve the absorption further, contributions were added by us in order to obtain better absorption.

Chapter I: Elements in Electromagnetics

Introduction

Before discussing the physics behind met materials, it is first pertinent to give a brief overview of electromagnetic theory [1]. The best way to understand the interaction of light wave and matter and the impact of signs of ε and μ on the propagation properties of materials is to study Maxwell's equations in an isotropic medium, which is controlling by the behavior of a wave in a medium [2]. Solving these equations is an introduction to electromagnetic waves, which in turn are absorbing by absorbers that mainly deal with electromagnetic waves and the latter are dividing into several radiations, such as, Terahertz (THz) radiation is defining by electromagnetic waves in the frequency band between the microwave and infrared regions ($1 - 10$ THz;$300 - 30\ \mu m; 4 - 40\ me\ V$) [3]. THz radiation has applications in many different research areas and shows much promise for a range of industrial, medical [4] and communications applications [4].

1. Maxwell's Equations

In Maxwell's Equations, you will find two kinds of electric field: the electrostatic field produced by the electric charge and the induced electric field produced by a changing magnetic field [6]. Maxwell's equations form the basis of all interactions between matter and light. In 1865, James Clerk Maxwell [7] devised four main equations, as follows [8]:

1.1 Gauss's Law for Electric Fields

Gauss's law for electric fields deals with the electrostatic field, and you will find this law to be a powerful tool because it relates the spatial behaviour of the electrostatic field to the charge distribution that produces it [6].

$$\nabla\ .\ \vec{D} = \rho \qquad (1)$$

1.2 Gauss's Law for Magnetic Fields

Gauss's law for magnetic fields is similar in form but different in content from

Gauss's Law for electric fields. For both electric and magnetic fields, the integral form of Gauss's law involves the flux of the field over a closed surface, and the differential form specifies the divergence of the field at a point [6].

$$\nabla . \vec{B} = 0 \qquad (2)$$

1.3 Faradays Law

In a series of epoch-making experiments in 1831, Michael Faraday demonstrated that an electric current might be inducing in a circuit by changing the magnetic flux enclosed by the circuit. That discovery is making even more useful when extended to the general statement that a changing magnetic field produces an electric field. Such ''induced'' electric fields are very different from the fields produced by electric charge, and Faraday's law of induction is the key to understanding their behavior [6].

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \quad (3)$$

1.4 The Ampere–Maxwell Law

In 1820, French physicist Andre-Marie Ampere heard that in Denmark Hans Christian oersted had deflected a compass needle by passing an electric current nearby, and within one week, Ampere had begun quantifying the relationship between electric currents and magnetic fields. ''Ampere's law'' relating a steady electric current to a circulating magnetic field was well known by the time James Clerk Maxwell began his work in the field in the 1850s. However, Ampere's law knew to apply only to static situations involving steady currents. There is Maxwell's addition of another source term– a changing electric flux– that extended the applicability of Ampere's law to time-dependent conditions. More importantly, there are the presence of this term in the equation now called the Ampere–Maxwell Law that allowed Maxwell to discern the electromagnetic nature of light and to develop a comprehensive theory of electromagnetism [6].

$$\nabla \times \vec{H} = \frac{\partial \vec{D}}{\partial t} + \vec{J} \quad (4)$$

Where $\vec{E}$ is the electric filed intensity $(V\,.m^{-1})$,$\vec{H}$ is the magnetic field intensity $(A\,.m^{-1})$, $\vec{D}$ is the electric flux density (C/m^2),$\vec{B}$ is the magnetic flux density (Wb/m^2), $\vec{J}$ is the electric current density (A/m). While in a source-free medium, there is no net charge and no current, so $\rho = 0, \vec{J} = 0$ In addition, in an isotropic and homogeneous medium, the electromagnetic constitutive relationships are express as following [8]:

$$\vec{D} = \varepsilon_0 \vec{E} + \vec{P} = \varepsilon_0(1 + X_e)\vec{E} = \varepsilon_r \varepsilon_0 \vec{E} = \varepsilon \vec{E} \quad (5)$$

$$\vec{B} = \mu(\vec{H} + \vec{M}) = \mu(1 + X_m)\vec{H} = \mu_r \mu_0 \vec{H} = \mu \vec{H} \text{ J} \quad (6)$$

Where ε ,ε_r and ε_0 are the electric permittivity of absolute, relative and free space respectively, and μ, μ_r and μ_0 are the magnetic permeability of absolute relative and free space respectively.σ Is the conductivity expressed in S/m, X_e is the electric susceptibility, X_m is the magnetic susceptibility. Thus, we can rewrite the Maxwell equations as [8]:

$$\nabla \,.\, \varepsilon \vec{E} = 0 \quad (7)$$

$$\nabla \,.\, \mu \vec{H} = 0 \quad (8)$$

$$\nabla \times \vec{E} = -\mu \frac{\partial \vec{H}}{\partial t} \quad (9)$$

$$\nabla \times \vec{H} = \varepsilon \frac{\partial \vec{E}}{\partial t} \qquad (10)$$

With electromagnetic filed $\vec{E} = E_0 e^{-i\omega t}$ and $\vec{H} = H_0\, e^{-i\omega t}$, substitute into the above equations, we can get [8]:

$$\nabla \times \vec{E} = i\omega\mu\vec{H} \qquad (11)$$

$$\nabla \times \vec{H} = -i\omega\varepsilon\vec{E} \qquad (12)$$

Then, the wave equation for an isotropic and homogeneous medium can be derive as following [8]:

$$\nabla \times (\nabla \times \vec{E}) - k^2\vec{E} \qquad (13)$$

Where $k = nk_0$ the wave number, k_0 is the wave number of free space, n is the refractive index of the medium, which they defined as following [8]:

$$n = \sqrt{\varepsilon_r\, \mu_r} \qquad (14)$$

Generally, permittivity and permeability can we expressed to be complex and dispersive as function of frequency, i.e. $\varepsilon(\mathrm{w}) = \varepsilon_1(w) + i\varepsilon_2(w)$ and $\mu(w) = \mu(w) + i\mu_2(w)$.so the wave impedance can we expressed as following [8]:

$$Z = \sqrt{\frac{\mu}{\varepsilon}} \qquad (15)$$

Most materials that exist in nature are characterized by positive ε andμ . A negative index of refraction can we obtain if, ε and μ and are simultaneously negative. A material with negative index of refraction is knew as left-handed material and exhibits backward wave propagation, i.e. the wave vector is opposite to the poynting vector, as shown in (Figure 1.1) [8]:

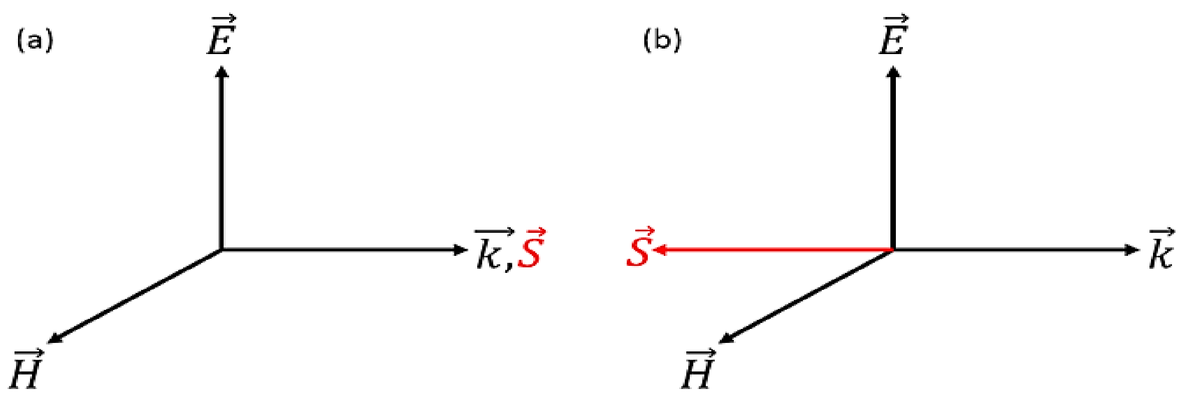

Figure 1.1: (a) Right-handed media: $\vec{S}$ and $\vec{k}$ in same direction. (b) Left-handed media: $\vec{S}$ and $\vec{k}$ in opposite direction [8].

The permittivity and permeability of materials are essential to predict the electromagnetic response. The materials performance to electromagnetic fields we are thoroughly determined by the values of them.(Figure 1.2**)** shows four possible combinations ε and μ of materials [8].

I.$\varepsilon > 0, \mu > 0$: A medium satisfies this condition is called double positive medium (DPM). Electromagnetic waves can propagate through the media with both positive permittivity and permeability. If the medium has complex permittivity, waves will propagate and decay in the medium [8].

II.$\varepsilon < 0, \mu > 0$: A medium with negative permittivity and positive permeability is termed as epsilon negative (ENG) material. Many plasmas display this characteristic. Noble metals are common ENGs in the infrared and visible frequency region [8].

III. $\varepsilon < 0, \mu < 0$: A medium that has both negative permittivity and permeability they named a double negative (DNG) medium. It is they, also called left-handed medium. Media with this property do not exit in nature. They have been demonstrate in artificial structures. The direction of the wave propagation is opposite to the wave-poynting vector ($\vec{E} \times \vec{H}$) [8].

IV.$\varepsilon > 0, \mu < 0$: Materials with positive permittivity and negative permeability can decay incident waves evanescently and cannot sustain propagation modes. They called permeability negative (MNG) media. Some ferromagnetic materials with resonances in microwave region have this phenomenon [8].

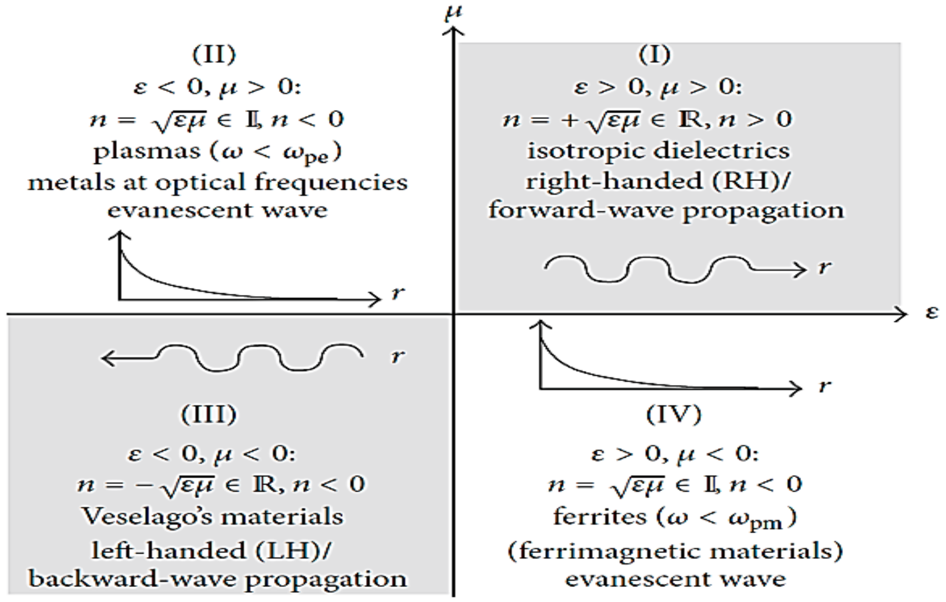

Figure 1.2: Combinations of materials electric permittivity and magnetic permeability [9].

2. The wave equations

With the differential form of Maxwell's Equations and several vector operator identities in hand, the trip to the wave equation is a short one. Begin by taking the curl of both sides of the differential form of Faraday's law

$$\vec{\nabla} \times \left(\vec{\nabla} \times \vec{E}\right) = \vec{\nabla} \times \left(-\frac{\partial \vec{B}}{\partial t}\right) = -\frac{\partial\left(\vec{\nabla} \times \vec{B}\right)}{\partial t} \quad (16)$$

Notice that the curl and time derivatives have been interchange in the final term, as in previous sections, the fields they assumed sufficiently smooth to permit this [6].

Another useful vector operator identity says that the curl of the curl of any vector field equals the gradient of the divergence of the field minus the laplacian of the field [6]:

$$\vec{\nabla} \times \left(\vec{\nabla} \times \vec{A}\right) = \vec{\nabla}\left(\vec{\nabla}.\vec{A}\right) - \nabla^2 \vec{A} \quad (17)$$

This relation uses a vector version of the laplacian operator that is they constructed by applying the to laplacian the components of a vector field [6]

$$\nabla^2 \vec{A} = \frac{\partial^2 A_x}{\partial x^2} + \frac{\partial^2 A_y}{\partial y^2} + \frac{\partial^2 A_z}{\partial z^2} \quad \text{(Cartesian).} \quad (18)$$

Thus,

$$\vec{\nabla} \times \left(\vec{\nabla} \times \vec{E}\right) = \vec{\nabla}\left(\vec{\nabla}.\vec{E}\right) - \nabla^2 \vec{E} = -\frac{\partial\left(\vec{\nabla} \times \vec{B}\right)}{\partial t}. \quad (19)$$

However, you know the curl of the magnetic field from the differential form of the Ampere–Maxwell law [6]:

$$\vec{\nabla} \times \vec{B} = \mu_0 \left(\vec{J} + \varepsilon_0 \frac{\partial \vec{E}}{\partial t}\right). \quad (20)$$

So,

$$\vec{\nabla} \times \left(\vec{\nabla} \times \vec{E}\right) = \vec{\nabla}\left(\vec{\nabla}.\vec{E}\right) - \nabla^2 \vec{E} = -\frac{\partial\left[\mu_0\left(\vec{J} + \varepsilon_0(\partial \vec{E}/\partial t)\right)\right]}{\partial t}. \quad (21)$$

This looks difficult, but one simplification can be achieve using Gauss's law for electric fields [6]:

$$\vec{\nabla}.\vec{E} = \frac{\rho}{\varepsilon_0}, \quad (21)$$

Which means

$$\vec{\nabla} \times \left(\vec{\nabla} \times \vec{E}\right) = \vec{\nabla}\left(\frac{\rho}{\varepsilon_0}\right) - \nabla^2 \vec{E} = -\frac{\partial\left[\mu_0\left(\vec{J} + \varepsilon_0(\partial \vec{E}/\partial t)\right)\right]}{\partial t} \quad (22)$$

$$= -\mu_0 \varepsilon_0 \frac{\partial \vec{J}}{\partial t} - \mu_0 \varepsilon_0 \frac{\partial^2 \vec{E}}{\partial t^2}.$$

Gathering terms containing the electric field on the left side of this equation gives

$$\nabla^2 \vec{E} - \mu_0 \varepsilon_0 \frac{\partial^2 \vec{E}}{\partial t^2} = \vec{\nabla}\left(\frac{\rho}{\varepsilon_0}\right) + \mu_0 \frac{\partial \vec{J}}{\partial t}. \quad (23)$$

In a charge- and current-free region, $\rho = 0$ and $\vec{J} = 0$, so [6]

$$\nabla^2 \vec{E} = \mu_0 \varepsilon_0 \frac{\partial^2 \vec{E}}{\partial t^2}.$$

(24)

This is a linear, second-order, homogeneous partial differential equation that describes an electric field that travels from one location to another in short, a propagating wave. Here is a quick reminder of the meaning of each of the characteristics of the wave equation [6]:

Linear: The time and space derivatives of the wave function ($\vec{E}$ in this case) appear to the first power and without cross terms.

Second-order: The highest derivative present is the second derivative.

Homogeneous: All terms involve the wave function or its derivatives, so no forcing or source terms are present.

Partial: The wave function is a function of multiple variables (space and time in this case) [6].

A similar analysis beginning with the curl of both sides of the Ampere Maxwell law leads to

$$\partial^2 \vec{B} = \mu_0 \varepsilon_0 \frac{\partial^2 \vec{B}}{\partial t^2}, \tag{25}$$

Which is identical in form to the wave equation for the electric field [6].

This form of the wave equation does not just tell you that you have a wave– it provides the velocity of propagation as well. It is right there in the constants multiplying the time derivative, because the general form of the wave equation is this

$$\nabla^2 \vec{A} = \frac{1}{v^2} \frac{\partial^2 \vec{A}}{\partial t^2} \tag{26}$$

Where v is the speed of propagation of the wave. Thus, for the electric and magnetic fields

$$\frac{1}{v^2} = \mu_0 \varepsilon_0, \tag{27}$$

Or

$$v = \sqrt{\frac{1}{\mu_0 \varepsilon_0}}. \tag{28}$$

Inserting values for the magnetic permeability and electric permittivity of free space,

$$v = \sqrt{\frac{1}{[4\pi \times 10^{-7} \mathrm{m\ kg}/C^2\ ]\ [8.8541878 \times 10^{-12} C^2 s^2/\mathrm{kg}\ m^3]}}, \tag{29}$$

Alternatively

$$v = \sqrt{8.987552 \times 10^{16} m^2/s^2} = 2.9979 \times 10^8 m/s. \tag{30}$$

It was the agreement of the calculated velocity of propagation with the measured speed of light that caused Maxwell to write, ‘‘light is an electromagnetic disturbance propagated through the field according to electromagnetic laws’’ [6].

3. Terahertz overview

Terahertz radiation is define by electromagnetic waves in the frequency range between the microwave and infrared regions [5] (0.1-30) THz (from 3 mm to 10 µm). Has gained interest of researchers due to its unique spectral properties [10]. For example, in astronomy, the THz emission and absorption spectrum of molecules have been use for space exploration. In medicine and security, THz radiation has been use for human body imaging with lower health risks compared to X-ray radiation. Moreover, THz radiation provides carrier frequencies higher than those used in current commercial wireless communication systems and has been use to increase channel capacities for short-range ultra-broadband communication. Various promising applications have made the THz region a growing research topic in the last decades. The useful applications mentioned above require the support of investigations on material properties that are important for THz devices. Researchers interested in the THz region have investigated properties of materials with different dimensions. In terms of traditional three-dimensional materials, such as silica and gold, their permittivity and conductivity have been characterised at the THz spectrum. Moreover, a set of two-dimensional (2D (Two-Dimensional)) materials, discovered in recent years, such as graphene, phosphorene, borophene, silicene, transition-metal dichalcogenides have also [11] been investigate [12].

3.1 The Terahertz Region

The terahertz region is located between the microwave and infrared regions. Its small wavelength, while still being non-ionizing, makes it ideal for a wide range of imaging and communications applications, along with many others [13].

In 2002, the spectrum ranging from 0.3 THz and 30 THz was propose as the “terahertz gap” due to the lack of devices working as sources or detectors. Three years later, the THz gap is the spectrum in the region from 0.1–10 THz, with wavelengths from 3 mm to 30 µm [11]. New advances in different technologies [4] have made the previously unused terahertz frequency band accessible for imaging systems [14]. The terahertz radiations are invisible to naked eye and in comparison with X ray [11]; they are intrinsically safe, non-destructive [14] and non-invasive [15]. This is such a new field that researchers around the world race to build the first practical System [14].

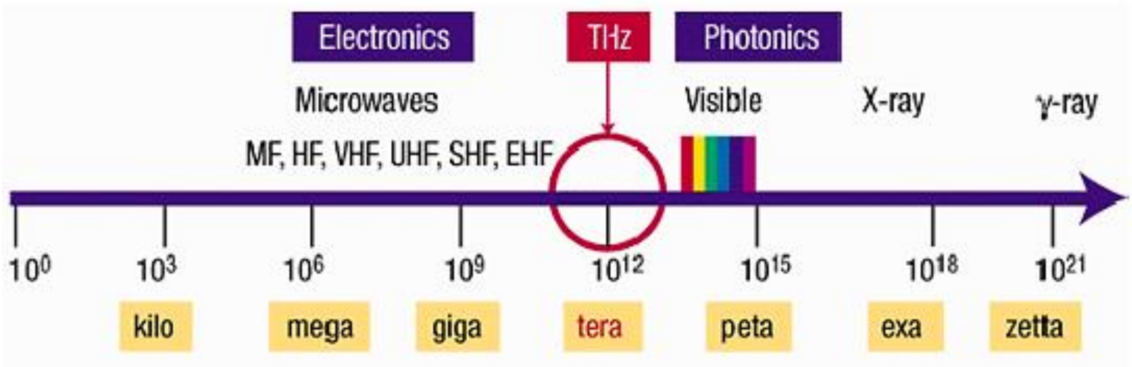

Figure 1.3: Terahertz Radiation within the Electromagnetic Spectrum [16].

3.2 Examples of Terahertz Applications

Terahertz (THz) regime, which has inherent advantages in civil and military applications, is widely applied in detectors [17], sources, imaging, sensors, and security systems [18]. Since few nature materials can respond to THz frequency, the potential payoffs of metamaterials drive a great of interest in THz-related applications [19], and one of the standout applications for THz radiation is in material characterization, with low energy THz photons suitable for probing electronic excitations and vibrational modes in solids.

As well as vibrational and rotational transitions in molecules [20]. Other applications involve the use of THz radiation in gas spectroscopy [15], for the characterization of fundamental semiconductor physics, and for the monitoring of industrial processes such as the manufacture of pharmaceuticals or the characterization of thin film paint thicknesses. Due to the non-ionizing nature of THz radiation, there is significant interest in THz medical imaging. In addition, due to the frequency being much higher than standard microwave carrier is frequencies, there are exciting opportunities to exploit the unused sub-THz and THz frequency bands to shape the future of wireless communication [21].

3.3 Terahertz instrumentation

Terahertz applications require sources and detection devices, as there has been significant progress in the development of such devices in recent years. One of the main challenges of developing THz instrumentation is that the frequency range falls between the normal operating limits of typical electrical and optical based components, resulting in the so-called THz Gap. Standard electrical microwave sources they limited by the carrier mobility of the oscillating semiconductor charges when increasing operation frequency, whereas for standard optical sources, there are significant challenges as the frequency is reduced into the THz region, particularly due to the lack of sufficiently small band-gap materials, as well as thermal considerations [22]. There is, however, been a significant move towards filling this

THz gap in recent years with significant breakthroughs in developing THz sources from the low frequency electrical side, as well as from the high frequency optical side. There are a number of solid-state voltage controlled diode oscillators, based on microwave technology, which are capable of operating above 1 THz, such as the impact ionization avalanche transit-time (IMPATT) diode, resonant tunnelling diode, and Gunn diode. However, as the frequency of operation increases, there is a sharp drop off in the output power [23], with power levels above the $m\,W$ level difficult to achieve in the THz region [24]. The most powerful demonstrated THz source is the free electron laser, capable of producing 100s of Watts of output power. However, these lasers are bulky, requiring the use of a linear accelerator as well as strong magnetic fields, and have a high power consumption that makes them impractical for most applications. Another electron beam based source is the backward wave oscillator, achieving $mW's$ of power [25]. A solid state high power source, operating in the high frequency THz region, is the quantum cascade laser (QCL) [24] which utilizes the inter sub-band transition of quantum well hetero-structure, demonstrating peak output powers $> 1\,W$. These lasers require cryogenic cooling, however, QCL sources, which operate by exploiting difference frequency generation using two infrared (IR) active regions, are a potential way forward for realizing high temperature operation of THz QCLs. Other source designs involve the use of a physical medium to convert optical laser power into emitted THz power. Optical parametric down-conversion can be achieve using a nonlinear crystal to produce THz radiation from a single incident source. Alternatively, two far-infrared pump lasers they can used to produce THz radiation via heterodyne mixing [26]. Photoconductive antennas (PCA) which consist of a metal antenna design on a photoconductive substrate, can be used to effectively produce CW THz generation by photo-mixing two frequency offset incident pump lasers. Some antennas they can also be used for THz pulse generation using a single femtosecond laser [27] as well as for THz detection, forming the building blocks of the important THz time domain spectroscopy (TDS) system. The following section will document the range of THz components used in this thesis to characterize and test the fabricated devices, which include a THz TDS system and THz QCLs [5].

4. Absorption

4.1 General Principals

When an electromagnetic wave impinges on a structure, it reflected, transmitted, or absorbed [28]. Assuming that the surface has an average roughness (Ra) that is much smaller than the characteristic wavelength so that there is no scattering from the roughness, incident wave may be reflected [R (ω)], transmitted [T (ω)], or absorbed [A (ω)]. According to Kirchhoff's rule, the sum of the transmittance, reflectance and absorbance must follow the relationship given as

$$A(\omega) = 1 - R(\omega) - T(\omega). \quad (31)$$

By solving Maxwell's equations inside the ambient medium and vacuum together with the boundary condition of the field continuity, it is easy to obtain the complex amplitude reflection moreover, transmission coefficient. When a plane wave propagating in a homogeneous medium encounters an interface with a different medium, a portion of the wave reflected from the interface while the remainder of the wave transmitted [29].

4.2 Fresnel Equations

The connection is made between the motion of charges on a microscopic level and optical parameters that we associate with macroscopic media, we still hope to connect these to quantities that are measured experimentally, such as transmission (T (ω)) and reflection (R (ω)). To do this, we must take into account the dynamics of light crossing from one media to another with different optical parameters, resulting in Fresnel's equations ،which represents the reflectivity at the air interface of a refractive medium the index n for transverse electric (TE) and transverse magnetic (TM) polarized waves is as follows [1]:

$$R_{TE} = \left|\frac{\cos\theta - (\mu_r)^{-1}\sqrt{n^2 - \sin^2\theta}}{\cos\theta + (\mu_r)^{-1}\sqrt{n^2 - \sin^2\theta}}\right|^2, \; R_{TM} = \left|\frac{\varepsilon_r\cos\theta - \sqrt{n^2 - \sin^2\theta}}{\varepsilon_r\cos\theta + \sqrt{n^2 - \sin^2\theta}}\right|^2 \text{ and} \quad (32)$$

$$T_{TE} = \left|\frac{2\cos\theta}{\cos\theta + (\mu_r)^{-1}\sqrt{n^2 - \sin^2\theta}}\right|^2 \left(\frac{\varepsilon_r\cos\theta_t}{n\cos\theta}\right), T_{TM} = \left|\frac{2n\cos\theta}{\varepsilon_r\cos\theta + \sqrt{n^2 - \sin^2\theta}}\right|^2 \frac{\varepsilon\cos\theta_t}{n\cos\theta} \quad (33)$$

Where $\theta$is the angle of incidence, $\varepsilon_r$and $\mu_r$are electric permittivity and magnetic permeability of the medium, respectively, and $n = \sqrt{\varepsilon_r\mu_r}$is the refractive index of the medium [29].

4.3 Absorption equation and impedance matching

Normally, the reflectivity of any surface can be calculate using Fresnel or many kinds of instruments. However, measuring the absorptivity of a surface needs special equations, because both transmission and reflection are involving. The absorption equation needed in both cases; simulation and measurements because many software do not calculate the absorption response. Therefore, the absorption equation needs they entered manually.

In order to characterize the absorption of any absorber, scattering parameters of reflection and scattering parameters of transmission should be they considered. Equation (34) used to calculate the absorption of the absorber and it derived from Fresnel equations [30].

$$|A(\omega)| = 1 - |S_{11}|^2 - |S_{21}|^2 \quad (34)$$

Where

A = Absorption.

S_{11} = Scattering parameter of reflection.

S_{21} = Scattering parameter of transmission.

For the simplified structure, the continuous ground plane blocks the electromagnetic waves and prevents any transmission through the structure [30]:

$$|\, S_{21}| \to 0 \quad (35)$$

Therefore, the absorption equation changes to

$$|A(\omega)| = 1 - |S_{11}|^2 \quad (36)$$

The simplified absorption equation (36) used in the following simulation and experimental sections.

The face of the structure or the surface impedance of the composite structure should be they designed in a way they matched to the free space impedance to obtain zero reflection on the surface interface [31]

Moreover, the interface material should have the specific impedance conditions to make the reflection as less as it can be [32]. To achieve perfect absorption without reflection, the surface impedance of the whole structure should be they constructed in a way to match to the intrinsic impedance in free space. The free space impedance can be calculate by the following equations:

$$Z_0 = \sqrt{\frac{\mu_0}{\varepsilon_0}} = \sqrt{\frac{4\pi\,.\,10^{-7}}{10^7/4\pi c^2}} = 377\Omega \quad (37)$$

WhereZ_0 is free space impedance, $\varepsilon_0 = 10^7/4\pi c^2\ Fm^{-1}$is the permittivity of the free space, $\mu_0 = 4\pi \cdot 10^{-7}\ Hm^{-1}$is the permeability of the free space. The surface impedance $\mathrm{Z}(\omega)$of the structure is calculate by the following equations [33]:

$$Z(\omega) = Z_0\sqrt{\frac{\mu_r(\omega)}{\varepsilon_r(\omega)}} = Z_0 \quad (38)$$

Where $\mu_r(\omega) = \mu_1 + \mathrm{i}\mu_2$is the complex relative magnetic permeability, and $\varepsilon_r(\omega) = \varepsilon_1 + \mathrm{i}\varepsilon_2$ is the complex relative electric permittivity [8].

4.4 Absorption mechanisms

Energy loss occurs in a medium illuminated by electromagnetic waves due to damping forces acting on polarized atoms and molecules. Vector calculus can they used to write an electromagnetic conservation-of-energy equation, referred to as the complex pointing vector theorem that relates the power flow into a volume V, via a closed surface S, to the electromagnetic fields and material properties contained within the volume. The real power flowing in such a surface is the dissipated (absorbed) power. To illustrate this statement, we report below the conservation-of-energy equation given by (39) derived from [34]

$$-\frac{1}{2}\iiint_V(\boldsymbol{H}^*\cdot\boldsymbol{M_i}+\boldsymbol{E}\cdot\boldsymbol{J_i}^*)dv=\oiint_S\left(\frac{1}{2}\boldsymbol{E}\times\boldsymbol{H}^*\right)\cdot d\boldsymbol{s}+\frac{1}{2}\iiint_V\sigma|\boldsymbol{E}|^2dv+ j2\omega\iiint_V\left(\frac{1}{4}\mu|\boldsymbol{H}|^2-\frac{1}{4}\varepsilon|\boldsymbol{E}|^2\right)dv \qquad (39)$$

Where $\boldsymbol{H}$ is the magnetic field intensity (in A/m), $\boldsymbol{M_i}$ is the impressed (fictitious source) Magnetic current density (in V/m^2) , $\boldsymbol{E}$ is the electric field intensity (in V/m), $\boldsymbol{J_i}$ is the impressed (source) electric current density (in A/m^2), σ is the conductivity (in S/m), ε is the complex permittivity (in F/m), and μ is the complex permeability (in H/m) Equation (40) can be written as (40)

$$P_S=P_e+P_d+j2\omega\left(\overline{W}_m-\overline{W}_e\right) \qquad (40)$$

Where

$P_s=-\frac{1}{2}\iiint(\boldsymbol{H}^*\cdot\boldsymbol{M_i}+\boldsymbol{E}\cdot\boldsymbol{J_i}^*)dv$: supplied complex power (W) (41)

$P_e=\oiint_S\left(\frac{1}{2}\boldsymbol{E}\times\boldsymbol{H}^*\right)\cdot ds$: Excited complex power (W) (42)

$P_d=\frac{1}{2}\iiint_V\sigma\,|\boldsymbol{E}|^2\,dv$: Dissipated real power (W) (43)

$\overline{W}_m=\iiint_V\left(\frac{1}{4}\mu\,|\boldsymbol{H}|^2\right)dv$: Time-average magnetic energy (J) (44)

$\overline{W}_e=\iiint_V\left(\frac{1}{4}\varepsilon|E|^2\right)dv$: Time-average electric energy (J) (45)

While P_s and P_e are in general complex and P_d is real, the last two terms are always imaginary and represent the reactive power associated with magnetic and electric fields. It should be emphasized that for complex permeability and permittivity, the contribution of their imaginary parts of the integrals of (44) and (45) should be combined with (43), as both represent losses associated with the permeability and permittivity as described in (46).

$$P_d=\frac{\omega}{4}\iiint_V\left(\mu''\,|\boldsymbol{H}|^2+\varepsilon''|\boldsymbol{E}|^2+\frac{\sigma}{\omega}|\boldsymbol{E}|^2\right)dv \qquad (46)$$

As a result, one can conclude that when the impedance matching condition is satisfied, to have total absorptivity, one or a combination of conductivity (σ), imaginary permittivity (ε''), and imaginary permeability (μ'') must be exploited [28].

5. Conclusion

The first chapter shows how Maxwell's Equations may be combine to produce the wave equation, the basis for the electromagnetic theory of light. The electromagnetic responses of materials to EM waves are critically determine by the material permittivity ε and permeabilityμ. They play an important role in the EM wave's propagation in the medium. Waves produce an electromagnetic spectrum that contains several radiations [6], so we will focus in this chapter on the terahertz radiation. The THZ region, typically designated between 0.1-10 x 10^{12} Hz, is in a region that has been designate as the "Terahertz Gap". This region provides potential for advanced imagery in the security, medical, and communications spheres, along with many others [35]. According to the interest of researchers from different communities, the definition of the THz gap has varied over the past 16 years. However, the definition has been within the range of 0.1 THz and 30 THz in most situations. In this thesis, the THz region it is defined as 0.1–30 THz due to the properties of GRAPHENE and GRAPHENE-based devices, which are studied in the following chapters [12].

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Chapter II: Theory of Absorbers

Introduction

The motivation to study absorbers for absorbing electromagnetic waves is due to their effective and important use in many potential applications in various fields, such as: emitters, sensors, spatial light modulators, IR camouflage anechoic chambers and wireless communication [1]. They are present in the aforementioned applications through different classical and commercial categories, which are dielectric, structural, resonant, magnetic [2] and metamaterial. Each category has developed through different scientific research, but in this memorandum, the category of Metamaterials they has been study due to the extent of their ability to miniaturize and their superior effectiveness in ideal absorption.

1. Electromagnetic-Wave Absorbers

The EM-wave absorber refers to structures that can absorb an incident EM wave based on the principles of transforming the incident EM-wave energy into Joule heat or canceling mutually the phases between the incident EM wave and the reflected wave, from microwave through optical frequencies.

Absorbers are required in many applications, an object that completely absorbs all light wavelengths they known as a black body, and carbon they considered as nearly a black body. As for sound wave environments, sound-absorbing materials they have often utilized, and glass fibers, rock wools, etc. They have used as materials that absorb sound waves well. Thus, even before the EM-wave absorber they developed objects that they can referred to as "absorbers" they have used in various scenarios in our daily lives. The study of wave absorbers is said to date back to the study of EM-wave absorbers for the 2-GHz band carried out in the mid-1930s at the Naamlooze Vennootschap Machinerieen in the Netherlands. Ever since the various types of EM-wave absorbers they developed, mostly for anechoic chamber applications and solar cells, photodetectors and so forth. They have been composed of carbon-based materials.

Interest in absorbers of electromagnetic radiation largely began around the second half of the last century during World War II (WWII), and their importance in this connection was considerable. The high attenuation of radar possible with such absorbers enabled military advantages and consequently great technical progress they made. The role played by the materials themselves was primarily utilitarian and little attention they paid to the scaling or universality of absorbers for their intrinsic interest. For example, radar they successfully used to find U-boats leading to losses. This in turn led to the development of radar absorbing materials (RAM) as an attempt to hide U-boat conning towers and periscopes. Two types of RAM were used—one termed a Wesch material, consisting of rubber sheets with carbonyl iron powder (commercially available before WWII), and the other a Jaumann absorber. Research into RAM they also undertaken as a means to increase the performance of radar systems. That is, it they applied to reflecting and scattering surfaces near the radar system, thereby reducing system noise. However, the approach used here was focused on anti-radar paints—called Halpern anti-radar paint (HARP) which also used iron particles—as well as Salisbury absorbers [3].

2. Absorbers

Conventional absorbers are usually composed of multilayer structures that are lossy and bulky; the motivation for studying absorbers comes mainly from their efficient use in potential applications. These applications include emitters, sensors, spatial light modulators, IR (infrared) camouflage, anechoic chambers and wireless communication. Absorbers in the mentioned applications they presented through different classical and commercial categories: dielectric, structural, resonant, magnetic and metamaterial. Each category they developed by different scientific researches, but the modern system requires miniaturized and compact absorbers. Metasurface-based absorbers are a good catch for their low profile, lightweight and simplicity of construction with simple metallic structures [1].

3. Classifications of Absorbers

In this section, we sum up the main absorber categories presented historically.

As is well known, EM-wave absorbers they classified according to various factors such as the structure, the material they used, and the frequency band they applied [4], but in this thesis, we will focus on the classification according to the material used.

3.1 Classifications of Material

Wave-absorbing materials that they have used since the invention of the wave absorber include several materials, and they divided into several classifications.

3.1.1 Conductive Absorber Material

Wave absorbing materials that they have used since the discovery of wave absorbers consist of loss-conducting metallic materials, resistive powders ،and resistive films. These they can said to be typical EM-wave absorbers. This is because they based on the principle of changing the currents generated in the absorber by the incident wave into Joule heat. As conductive wave-absorbing materials, there exist materials having predetermined resistance values. These are composed mainly of carbon-based materials such as carbon black or graphite. They are widely used in the form of platelike or filmlike materials for the conductive type of wave absorber material. Furthermore, excellent EM-wave-absorbing characteristics they realized if using a specific conductive fabric. A typical example of an EM-wave absorber using a resistive conductive material is a $\lambda/4$-type wave absorber, which is a basic EM-wave absorber configuration [4].

3.1.2 Dielectric Absorber Material

This type of absorber is basic [5]. Examples of dielectric wave-absorbing materials are carbon rubber, carbon containing urethane foam, and carbon-containing expanded polystyrene. These materials they made by mixing carbon material with rubber, urethane, etc. [4]. These materials they realized to have the highest dielectric loss constant thus, transforms into heat the maximum of the incident wave [5]. This kind of material they used to realize broadband absorption characteristics and they applied to multilayer-structure, wedge, or pyramid types of wave absorbers [4], the impedance of this type of material is not strongly adapted to the impedance of the free space, and thus, they can present a strong reflection at their interface. However, these absorbers have several negative aspects, including: loss in performance, is purely dielectric with no magnetic properties because of their lack of magnetic absorption, they do not perform well for most cavity resonance applications, which is the drawback of dielectric absorber [5].

3.1.3 Magnetic Absorber Material

Magnetic absorbers use a filler material that has ferromagnetic properties and has high Permeability and high magnetic loss [6]. A thin wave absorber configuration can be realized using ferrite, carbonyl iron, and the like, which are magnetic loss materials available at frequencies higher than the very high frequency(VHF)band .In this case ,the EM-wave-absorbing characteristic is strongly governed by the frequency dispersion characteristic of magnetic material and, thus, by permeability value [4]. Magnetic absorbers are best for cavity resonance damping because the magnetic field is a maximum on the conductive surface. However, cost and weight are the disadvantage of magnetic absorbers [6].

3.1.4 Resonant Absorber

They called also tuned absorber. They include the Dällenbach layer, Salisbury and Jaumann layers [7]. In this class of materials, the impedance is not necessarily adapted between the medium of the incident wave and the absorbing one. These materials are thin and do not absorb all the energy to which they are subjected. They operate through the destructive interference of the reflected waves [2].

3.1.5 Structural Absorbers

It they known that a wave is reflected at the interface of the material proportionally to the impedance of the latter. From this observation, three categories of absorbers (pyramidal, progressively loaded and impedance matching layers) were developed to improve the diffusion of the wave in a dielectric absorbing layer. For good attenuation over a wide band, this type of material requires large thickness with a significant weight [2].

3.1.5.1 Pyramidal Absorbers

Pyramid absorbents are thick meterials with regularly spaced structures of pyramidal or conical shape and positioned perpendicular to the surface [8]. The impedance of the pyramidal absorbers is gradually changed, almost corresponds to the free space impedance in the end [9]. The height and frequency of the pyramid must be in the order of wavelength. If the absorber has a longer wavelength ,the incident wave will encounter unexpected changes in impedance, leading to a reduction in the minimum operating frequency ,periodicity and height of this structure depend on the wavelength .the performance of pyramidal absorbers is very good , but their disadvantage is that they are thick , sensitive and fragile [6]. As shown in the figure (2.1):

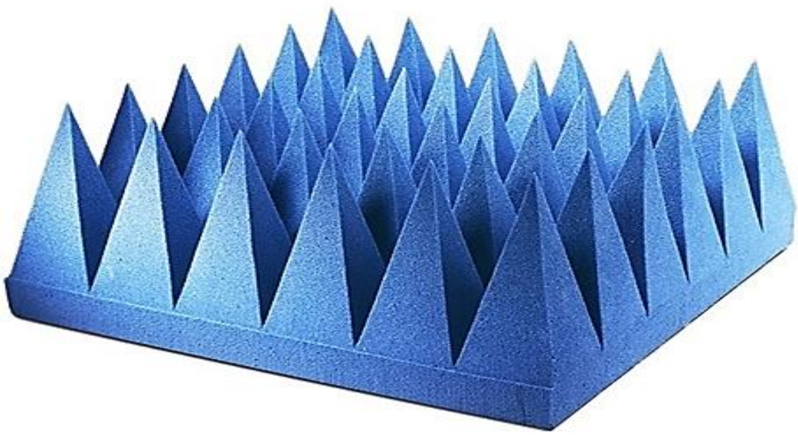

Figure 2.1: Illustration of Pyramidal Dielectric Absorber [2].

3.1.5.2 Taped Loaded Absorber

In general, this type of material consists of a plate of a low loss material associated with a plate of a material with high losses. The advantage of these materials is that they are thinner than pyramidal absorbers but less efficient [5].As shown in the figure (2.2)

3.1.5.3 Matching Layer Absorber

The matching layer absorber gradually reduces the required thickness of the loaded material.

This type of absorber provides an absorption transition layer between the incident wave and the absorbent materials. The transition layer has an impedance value between the impedances of the two media. A feature they intended to be an impedance transition between different environments. This matching they achieved directly with the thickness of the layer corresponding to a quarter of the wavelength of the incident wave with:

$$Z1 = \sqrt{Z0 \times Z3} \quad (1)$$

Impedance matching only occurs at the specified frequency, because this type of absorber is narrow-band and very thick at low frequency [5]. As shown in the figure (2.2):

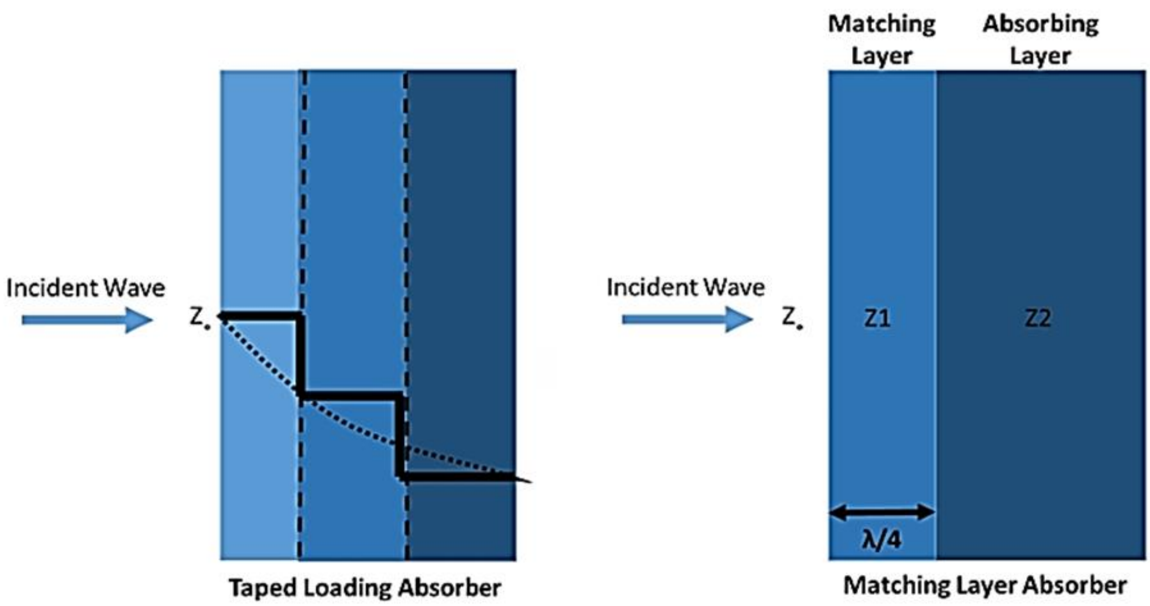

Figure 2.2: Illustration of Taped Loading Absorber and Matching Layer Absorber [2].

3.1.6 Reflectivity absorber

This type of absorption they classified into two main categories. When compared to an ideal reflector (metal plate), reflection absorbers reduce the level of reflection [6].

3.1.6.1 Reflectivity narrowband absorber

When the thickness of one layer of a homogeneous material is estimated as، It will create a resonate frequency. Therefore, the front surface of the material will partially reflect the incoming wave while transmitting part of it. This transmitted wave then propagates through to

Back of the absorber, it also has total reflection and they propagated again through the front face of the absorber. If the wave reflected wavefront is equal in magnitude and 180° out of phase with the reflected wavefront then the waves will cancel, Total reflection does not occur, but if we want it to happen, it is represented by the complete absorption of the wave within the material .

Impedance of the front surface ($Z = 0$ due to conductor) they must be matched to the free space impedance ($Z = 377\Omega$ due to free space). Therefore, the absorbers they designed such that the impedance they perfectly matched and complete absorption they obtained [6].

An example of this is the most common narrow band absorber, the Salisbury monitor composed of a resistive screen placed $\lambda/4$ distance from a metal sheet [6], as shown in Figure (2.3):

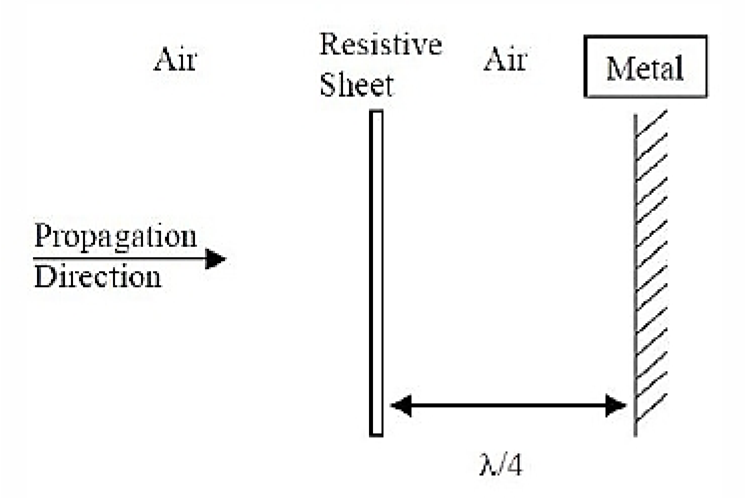

Figure 2.3: Salisbury screen [6].

3.1.6.2 Reflectivity Broadband absorber

There are several types of broadband reflective absorbers that discussed would in the following section:

(a) Multi-layer absorbers:

Multi-layer absorber design techniques are a quarter-wave transmission technique, where impedance matching is achieved in the stacked forming the insulating layers, and this leads to providing a greater frequency range [6].

(b) Jaumann absorbers:

In order to achieve better performance and overcome the limitations of Salisbury screens, Jaumann pipettes they designed. It contains multiple resistive layers in addition to conductive materials, and the multiple layers they used to increase the absorption bandwidth [10]. As shown in the figure (2.4):

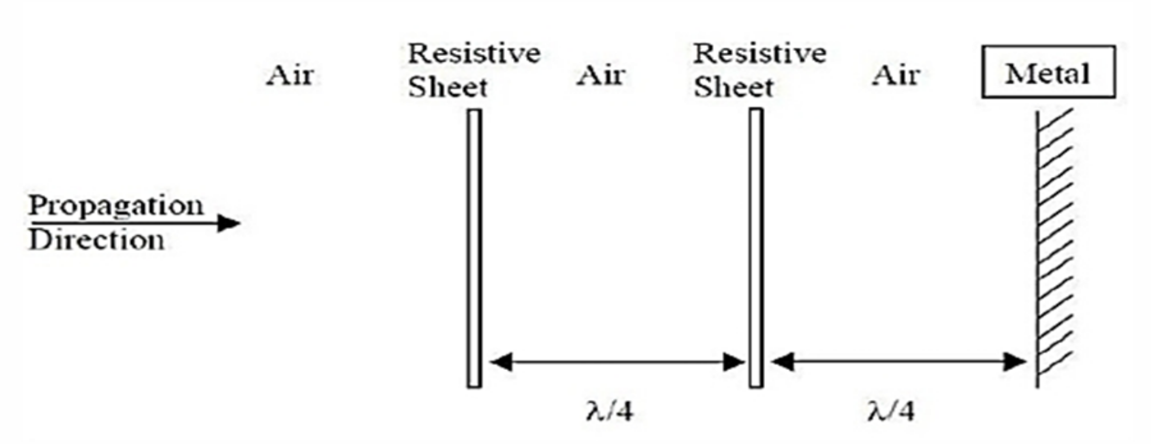

Figure 2.4: Jaumann absorbers [6].

3.1.7 Metamaterials absorber MMA

Negative index materials generated a great deal of hype and scientific research into MMS in the early 2000s. However, very quickly it they realized that Metamaterials could go beyond negative index, being capable of improving many desirable electromagnetic properties in a random frequency regime [11]. Metamaterial (MM) is defined as metamaterial is an arrangement of artificial structural elements designed to achieve unusual electromagnetic properties. The most common meaning of the term is "meta". In Metamaterials "beyond". From here, Metamaterials they can defined as artificially designed materials with distinctive, unique or abnormal properties that they cannot found in natural materials at the frequencies that they will studied. A very important application of these structures is the ideal absorption that they can provided when the transmissivity and reflectivity of these materials they simultaneously reduced to zero so that all incident electromagnetic radiation is absorbed by the material [12]. The first MMA they designed by Landy in2008 . The structure consists of three layers, two metallic layers separated by a dielectric. The top layer made of copper and formed in an electric ring resonator (ERR) that can supply the electric response along with the ground plane at a specific frequency by coupling the incident electric field. Figure 2.5**.** The ground plane metallic layer, consists of a copper cut wire which is separated from the top ERR by FR4 dielectric substrate layer. The antiparallel currents in the center of the ERR and the cut wire produces the magnetic coupling [13]. The frequency response of the structure related to the dimensions of the ERR and the thickness of the dielectric and it can be tuned. Demonstrates the perfect MMA designed by Landy and the incident wave's direction and the structure response. The blue, green, and red signals are signals for transmission, reflection, and absorption, respectively [14].

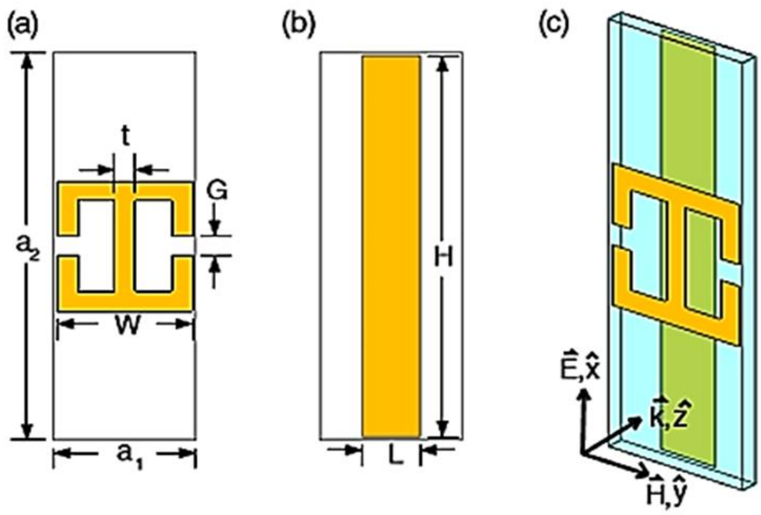

Figure 2.5: Electric resonator (a) and cut wire (b). The unit cell is shown in (c) with axes indicating the propagation direction [15].

4. Application of Wave Absorbers

There are several major applications of wave absorption and its associated materials, there are several major applications of wave absorption and its associated materials, and the application areas of electromagnetic wave absorption are expanding with the development of communications technologies. The most common of these applications is the absorption of waves in anechoic chambers, where many studies and research they have been conducted that contain the latest analyses such as what they related to the pyramid type or wedge absorbers. The studies they based on theories; experiments, the moment method, and the frequency-domain finite-difference method they have reported. Studies they have also applied. Careful experimental study of anechoic chambers. In addition, the process of treatment and study they carried out with the aim of improving radar technology because it they considered a very important focus in the field of absorption of electromagnetic waves.

Particularly relevant to radar problems, EM wave detectors they have used since the beginning of the development of gravity. It was necessary to take precautions against the faulty image problem on the radar screen caused by radar waves reflected from the high bridge over the sea. Absorption walls they have been developed for tall buildings in Japan because exposure to EM-TV waves from the top of building walls causes TV .Additionally, from the perspective of EM environmental protection in various consumer electronic products and LAN environments, EM wave attenuation measures have been evaluated, leading to the development of various types of attractors. Additionally, measures they needed to reduce the circuit board noise of the input device, which has been a problem in recent EM research. For these countermeasures, a plate- like layer was made of magnetic material, thin ferrite beads, and other active called noise [16].

5. Metamaterial based Perfect Absorber

Based on Fresnel coefficients, it they immediately revealed that a completely absorbing medium they described by electrical permittivity and magnetic permeability. With the aim of achieving perfect impedance matching over larger frequency ranges, the latter prompts one to engineer the value and dispersion of the electrical permittivity and magnetic permeability of the medium. Many metals around the plasma frequency also exhibit it. This leads to the design of sub-wavelength structures whose resonance can drive the magnetic component of the electromagnetic field. Due to the difficulty of finding these materials in nature, this is what prompted researchers to resort to artificially structured materials, because they its effective mean parameters they can be engineered to obtain the desired dispersion [17].

Landy et al designed the first ideal absorber using Metamaterials. A high absorption rate estimated at 99% they achieved at a frequency of 11.48 GHz. This absorber consists of several layers, the upper part is the ERR, which produces an electrical response by closely matching the electrical event to the desired line. The second layer, separated from the top by a dielectric, consists of wires cut in a parallel plane and contributes to the electrical response. On, the magnetic coupling is achieved through a circuit passing through the circuit breaker and the center wire of the ERR. The time-varying magnetic field can couple to these parallel resistive currents, creating a Lorentz-like magnetic response. Therefore, the basic principle by which absorption provides optimal absorption in a metamaterial is by tuning the magnetic resonance resulting from the structural design as well as the electrical response of the material. This results in providing excellent flexibility, strength and tunability they efficiently control the absorption of electromagnetic energy for this material. It is under the framework of a treatment that did not previously exist in nature [18].

6. Metamaterials

The working concept of electromagnetic structure been around long before the word metamaterial they coined. One of the most famous and earliest examples of Metamaterials is the Lycurgus cup, dating to the fourth century AD, and a type of dichroic glass similar to the glass used to impregnate stained glass [19]. At the time, the best glass materials they assembled by adding different types of powders during production, but a lack of understanding of the interaction between light and matter meant this was done by trial and error [20]. The term Metamaterials has its origins in a 1999 DARPA workshop, introduced by Walser M Rodger

[21]. The electromagnetic properties of natural or chemical materials they determined mainly by their chemical composition, that is, the atoms and molecules that compose them. In the metamaterial paradigm, the role of atoms or molecules they played by "meta-atoms", which are components of artificial materials. Meta atoms are macroscopic objects made of common materials (metals, dielectrics, etc.). As long as the size of the meta-atoms and the distance between them remain small enough to within the dimension of the diameter of interest, particles composed of meta-atoms can be considered 'materials' defined by physical properties (such as permittivity or permeability). The same macroscopic interpretation of the electromagnetic properties of matter in terms of permeability) and the relationship between elements can be applied to materials made from meta-atoms as well as to materials made from ordinary atoms or molecules. The electromagnetic response of meta-atoms determines their shape, internal structure, size, orientation, etc. they can used to determine accurately. Additionally, the response of individual meta-atoms they can be monitored and correlated with external signals. Alternatively, within this, programmable microprocessors, which open up the possibilities of designing flexible, time-sensitive, intuitive and software-defined artificial devices and surfaces. The main concept of Metamaterials stems mainly from the new possibilities of obtaining synthetic materials with electromagnetic properties not available in any natural material and engineering the ideal properties for specific applications. Thus, Metamaterials they can defined as effectively homogeneous artificial materials consisting of an arrangement of artificial structural elements designed to produce features Useful and unhelpful electromagnetism.

6.1 The effect of Metamaterials on the wave

Metamaterials can significantly manipulate the incident electromagnetic wave.

In addition to the effects on the incident wave, they exhibit unusual properties. (Negative refractive index, invisibility cloaking and so on) These features they not found in natural materials. The material properties are strongly dependent on their complex permittivity (ε) and complex permeability (μ) values which are provided in equation (2) and equation (3) correspondingly [23].

$$\varepsilon(\omega) = \varepsilon'(\omega) + i\varepsilon''(\omega) \tag{2}$$

$$\mu(\omega) = \mu'(\omega) + i\mu''(\omega) \tag{3}$$

These values are frequency dependent values. This means that the response is changing with the frequency. In general, the properties of the materials according to their electromagnetic characteristics they represented. The materials that have positive permeability and negative permittivity is the metals at optical frequencies and the plasmas while the dielectrics have both positive values of these quantities. The magnetic materials have permeability lesser than zero and electric permittivity greater that zero. These three types explained above are called right-handed materials and they be found in the nature. However, the ones that have both of the permittivity and the permeability negative they cannot found in the nature [24].

6.2 Applications of Metamaterials

Metamaterials have interesting electromagnetic properties; Metamaterials have interesting electromagnetic properties, as the discovery and development of these materials led to their applicability in many fields and research such as optics, communications, and energy harvesting. This section discusses about some example applications linked to Metamaterials.

The first application of MTMS devices is the realization of the first perfect invisible cloak, since the working mechanism of Metamaterials is capable of controlling electromagnetic fields. This contributed to a new invention, namely, “invisible cloak.” Based on the idea of light bending and coordinate transformation Pendry et al. proposed the first perfect invisible cloak. The most commonly used application of the property of Metamaterials in general is in the military field, where covered devices such as military aircraft, cars.

In addition, clothing are manufactured, by controlling, preventing, and completely blocking them from the emission of electromagnetic waves (such as radar and other remote sensing devices) emission, as a result the object can be hidden in it and remains undetectable [25].

The second potential use of MTMs is their unique role in the development of high-performance materials and antennas. Based on surface plasmonic resonance, Metamaterials they used to create flexible conductive systems. Typically, the surface plasmon phenomenon occurs at the interface between a metal and a dielectric. This phenomenon they strongly influenced by the decay rate of network connectivity and penetration in the deep field. Then; a change in the parameter of the dielectric constant changes the dispersion constant of the surface plasmon. The use of the coupling method leads to a change in the properties of the electromagnetic wave coupled to the surface plasmon [26].

Conclusion

In this chapter, a comprehensive overview of most of the facilities combined in the industry that work to absorb electromagnetic velocity in certain circumstances they presented. It may shed light on the advantages and frankness of each category, as part of the fact that the first category started us is the hierarchical integrated one provided by companies of high standing and these they intended for anechoic chambers, but this last sensor is fragile and has a long duration, especially at frequencies below 1 GHz. This prompted the creation of a new category of diamonds that work to attract likes well when needed better. Metamaterials work well using electromagnetic resonance, which results in absorption in a narrow frequency band that can limit their use. Hence, methods proposed in the literature for designing broad-based descriptive materials they presented [2].

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Chapter III: Results and discussion

Introduction

This chapter provides a general overview of the graphene material, and focuses on the distinctive properties of this material. The description of the graphene material they was confirmed through effective surface conductivity, and during simulation, the extent of the effect of the conductivity and structure of graphene on the value of absorption of electromagnetic waves in the terahertz field was known.

1. Discovery of Graphene

University of Manchester scientists have been carefully studying and manipulating inherent carbon elements for several years, finally reaching the breaking point of exposing a single layer of graphene through mechanical exfoliation of the graphite [1]. Based on this element, the concept of graphene they was derive.

2. Graphene

Recently, graphene has attracted the attention of researchers and scientists because it possesses excellent properties at the optical, electrical and mechanical levels. Graphene in particular is atoms of carbon that show strange and promising properties and have the ability to achieve major changes in the world of technology. After the discovery of this material in the year 2004, electrical properties, optical characteristics thermal features and mechanical properties shows promising results for the application in optical an terahertz realms .

The structure of graphene they considered a two-dimensional structure and they obtained in layers, because this material contains carbon atoms arranged correctly and symmetrically and with a depth of one atomic height. This is what gave it the structural characteristic of two dimensions. One layer of this material has about (0.335 nm) height [2].

2.1 Evolution of Graphene Material

Both scientists and engineers are working hard on graphene material because of its superior properties. It they believed that many new research topics related with graphene will continue to grow because it has many applications and different scholars are working on its development.

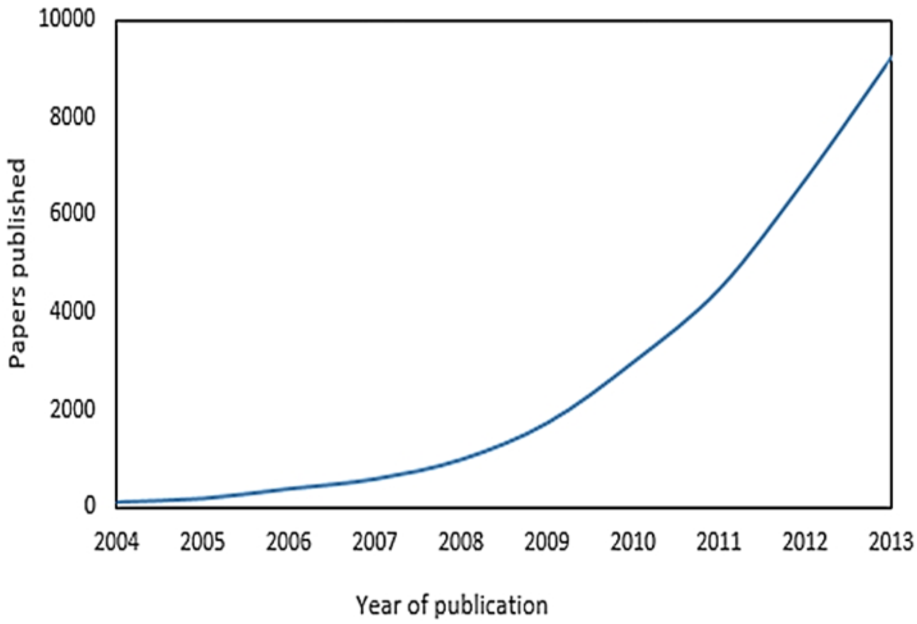


Figure 3.1: Growth in graphene related researches for a decade (2004-2013) after its discovery [5].

3. Properties of Graphene

Graphene they characterized by several optical, electronic, and mechanical properties, and each of these elements will be discussed in detail.

3.1 Electronic and Optical Properties of Graphene

Graphene they considered the thinnest material ever created, as it consists of bonds (s p^2)C-to-C bonds, which in turn they considered the strongest bond in chemistry. This is what makes this bonding property give graphene the advantage of strength and validity despite its thin thickness, which is valued at (0.345 nm) and its small density, which is valuable (0,77 mg per square meter) , Furthermore, the conduction band and valence band of graphene overlap and hence it is considered a zero band gap metal. Normally, a carbon atom has four electrons in its mass that participate in the bonding process, but in graphene only three electrons contribute to the bonding (giving graphene a structure and mechanics similar to that of diamond). Leaving the graphene with one free electron ($p_z$electron) is also responsible for electronic transport on the way to Z- direction and is responsible for electronic conduction.

The carbon atoms in graphene are arranged in a hexagonal lattice in a $2D$ –plane, where the shortest distance between atoms is $a_0 = 1.42$ Å . That is, each atom contains a π- bond that bonds together to give π-bonds and π^2- bonds and this bond they taken into account. For the surprising electronic properties of graphene materials. Graphene is not only very special, but it also exhibits other special electronic and optical properties, such as good diffraction properties and special electrical effects where carriers (electrons and holes) are concentrated at10^{13}cm^{-2}, while at room temperature it is$10^{4}\text{cm}^{2}V^{-1}s^{-1}$. It can reach $\text{cm}^{2}V^{-1}s^{-1}$. Graphene is one of the materials with the highest thermal conductivity, with the thermal conductivity of g of the monolayer reaching $5000\ \text{Wm}^{-1}\text{K}^{-1}$ at room temperature. Another important optical property of graphene, which plays an important role in the process of designing good Metamaterials, is its optical properties. Despite being a single atom, graphene has demonstrated the ability to increase the absorption by up to $2.3\%$for each additional layer of graphene in the absorbing state (the opacity of graphene$\pi\alpha = 2.3\%$, corresponding to the global given by $(\omega) = \frac{e^4}{4\hbar}$ e represents the electron charge and $\hbar = \frac{h}{2\pi}$, h is Plank's constant= $6.62606957 \times 10^{-34} m^2 \text{k}g\ s^{-1}$) in visible light. This is because of the electrons in graphene behave like the massless charge carries with a very high mobility [5]

4. Applications of Graphene

Studies and research applied to graphene material during these recent years have led to the emergence of many applications in different fields due to its exciting chemical and physical properties. Currently, many potential applications for graphene technology they have revealed more will come from ongoing research in this field, such as nanoelectronics, biosensors, chemical devices, energy storage, and clean energy devices [3].

5. Effective conductivity of graphene metamaterials

The properties of graphene they described mainly in terms of surface conductivity, and the quantity they measured directly in a wide range from radio frequencies to THz frequencies. The conductivity of graphene they also described by interband and intraband contributions [6].

$$\sigma_S = {\sigma_S}^{\text{intra}} + {\sigma_S}^{\text{inter}}, \quad (1)$$

$$ {\sigma_S}^{\text{intra}} = \frac{2\text{k}_B\text{T}e^2}{\pi\hbar^2}\ln(2\cosh\frac{E_F}{2\text{k}_B\text{T}})\frac{\text{i}}{\omega+\text{i}\tau^{-1}} , \quad (2)$$

$$ {\sigma_S}^{\text{inter}} = \frac{e^2}{4\hbar}\left[H\left(\frac{\omega}{2}\right) + \text{i}\frac{4\omega}{\pi}\int_0^\infty \frac{H(\Omega)-H\left(\frac{\omega}{2}\right)}{\omega^2-4\Omega^2}\text{d}\Omega\right], \quad (3)$$

Where $H(\Omega) = \sinh(\frac{\hbar\Omega}{\text{k}_B\text{T}})/\left[\cosh\left(\frac{\hbar\Omega}{\text{k}_B\text{T}}\right) + \cosh\left(\frac{E_F}{\text{k}_B\text{T}}\right)\right]$ is the temperature, E_F - electrochemical potential (Fermi energy), ω – frequency of the electromagnetic wave and $\tau = 10^{-13}s$ - the relaxation time .For the THz frequencies, where the photon energy,$\hbar\omega \ll E_F$,the interband part(3)is negligible comparing to the intraband .Therefore, in the THz range graphene is well described by the Drude –like surface conductivity(2).For $E_F \gg k_B T$ the conductivity depends linearly on the Fermi energy

$$\sigma_S \approx \frac{e^2 E_F}{\pi\hbar^2} \frac{i}{\omega + i\tau^{-1}}. \quad (4)$$

For the numerical simulations graphene they usually represented as a layer of material of a small thickness Δ with an in-plane effective permittivity

$$\varepsilon_{\mathrm{eff,t}} = 1 + i\frac{\sigma_S}{\varepsilon_0 \omega \Delta}. \quad (5)$$

The normal component of the effective permittivity $\varepsilon_{\mathrm{eff,n}} = 1$.

In other words, we can say a thin metal represents that graphene with the plasma frequency depending on the Fermi level

$$\omega_P = \left[\frac{2e^2 k_B T}{\pi\hbar^2 \varepsilon_0 \Delta} \ln\left(2\cosh\frac{E_F}{2k_B T}\right)\right]^{\frac{1}{2}}. \quad (6)$$

The conductivity of a continuous graphene film can be calculated analytically with expression (2).However, for structured graphene metamaterials an analytical description is problematic and

Therefore, we should turn to numerical methods .Tassin et al. [7] proposed to characterize the thin-film metallic and graphene metamaterials with the electric and magnetic effective surface conductivities $\sigma^{(e)}$ and $\sigma^{(m)}$ and proposed the formulas for their retrieval for the symmetric environment (the same homogeneous dielectric on the both sides from the Metasurface) [8].

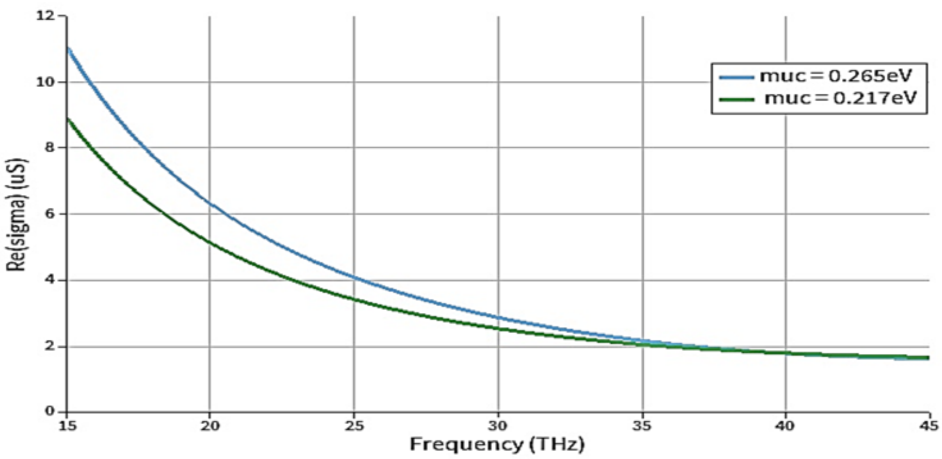


Figure 3.2: variation real value of conductivity with frequency of the electrical chemical potential [8].

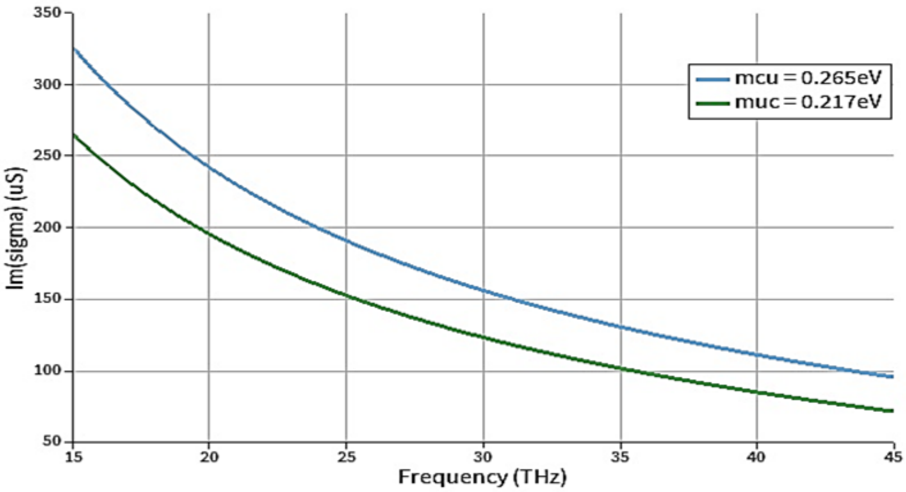


Figure 3.3: variation imaginary value of conductivity with frequency of the electrical chemical potential [8].

6. Tunable graphene metamaterial absorber

In this chapter, we re-simulated a previous study by one of the researchers; the application they made in the field of terahertz radiation this simulation sheds light on the absorbing material graphene. The absorption spectrum they also can adjusted by changing the chemical potential applied to the graphene.

Using the main software, ANSYS in order to implement this simulation, we directed plane wave radiation on an absorber consisting of an upper layer of graphene metal of very thin thickness, with an insulating material underneath it. The simulation field, which is an FDTD (Finite-difference time-domain) technique, is limited at the top by PML BC (perfectly matched layers boundary condition), and at the bottom, under the insulating material, we find metal of the type Metal BC. The absorber absorbs part of the transmitted radiation, part bounces back, and sensitive devices called Monitor measure the returned value. The study also takes place at a specific part because the edges of the study field are periodic BC (boundary condition).

The absorption value they calculated according to the following equation:

$$A = 1 - R - T \qquad (7)$$

As shown in the following figure (3.4).

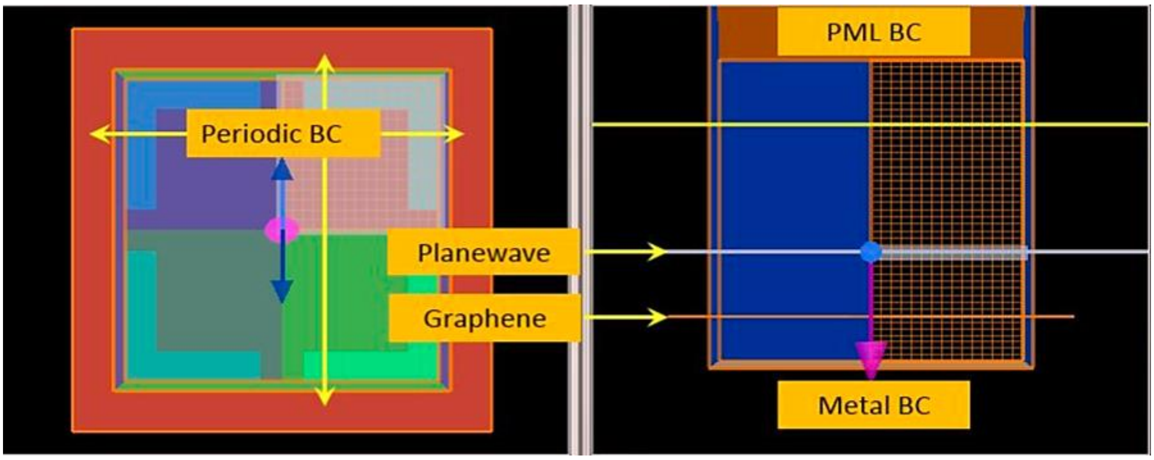


Figure 3.4: schematic view of absorber [8]

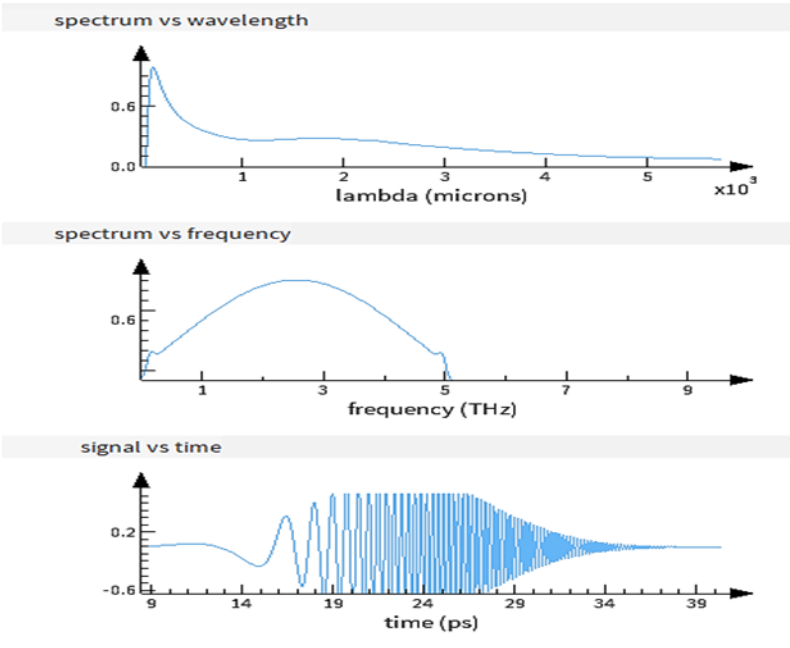


Figure 3.5: The form of radiation received from the source [8].

7. Simulation setup

It is also possible to get rid of the absorption spectrum of graphene by making a change in the main geometric parameters, as there are two types of structures that they will take into consideration during the study and simulation, which are uniform design and fishnet design. As shown in the following figure (3.6).

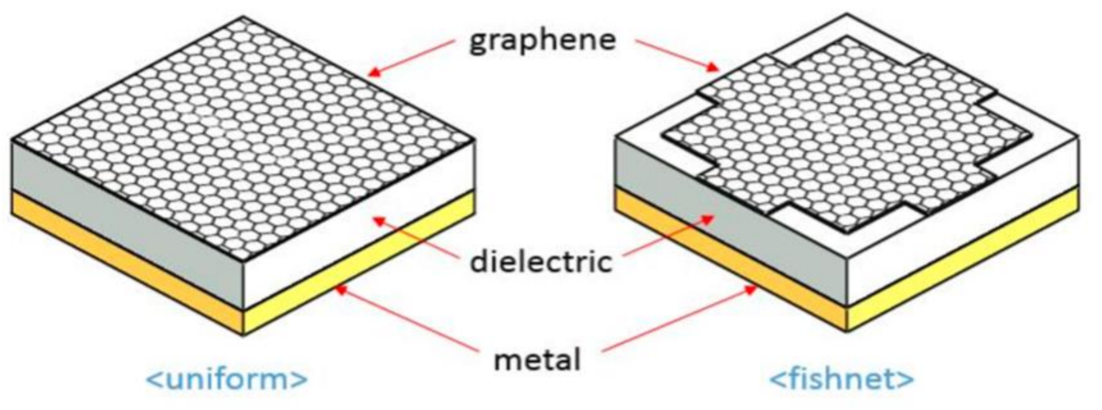


Figure 3.6: cross sectional view of the absorber [8].

We used it in both cases a 2D graphene material model based on the surface conductivity of the graphene [8].

7.1 simulation of uniform Design

In this example, we simulate a uniform structure, in order to calculate the two layers of graphene used, as we use a 2D rectangular object to model the sheet, and we do not need to add a mesh overflow region over the graphene to solve the thin layer.

The absorption spectra of the uniform structure as a function of the chemical potential [8].

Achieved these results as shown in the corresponding figure (3.7).

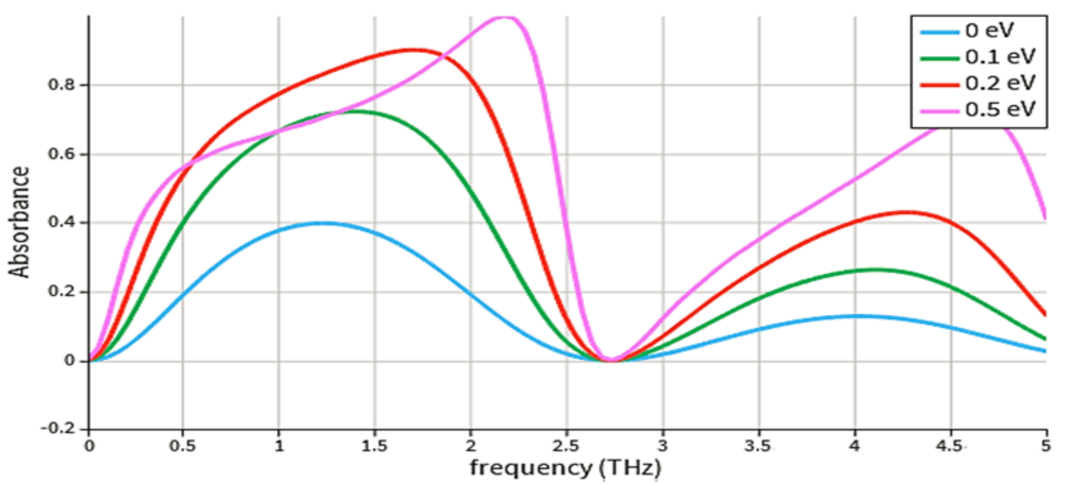


Figure 3.7: variation of absorbance with frequency for different valious the electrical chemical potential [8].

7.1.1 Results

As is already known, the absorption spectrum of graphene depends mainly on the chemical Potential of graphene itself, A change in the chemical properties of graphene can be achieved by applying a potential difference, where every time we change the value of the chemical potential and observe the rate of absorption with frequency. The change in the potential difference works to control the conductivity of graphene, as the greater the potential difference We notice an increase in the absorption rate, and the reason is due to the increase in the conductivity of graphene, but we obtained a dual band absorption spectrum, and to obtain a wider absorption spectrum, we use another structure [8].

7.2 simulation of Fishnet Design

In this technique, a change in the geometry of the fishing net metamaterial was made by using polygonal objects with a refractive index of 1.53 (corresponding to the background index for dielectric) were used to pattern the 2d graphene sheet [8]. Achieved these results as shown in the corresponding figure (3.8).

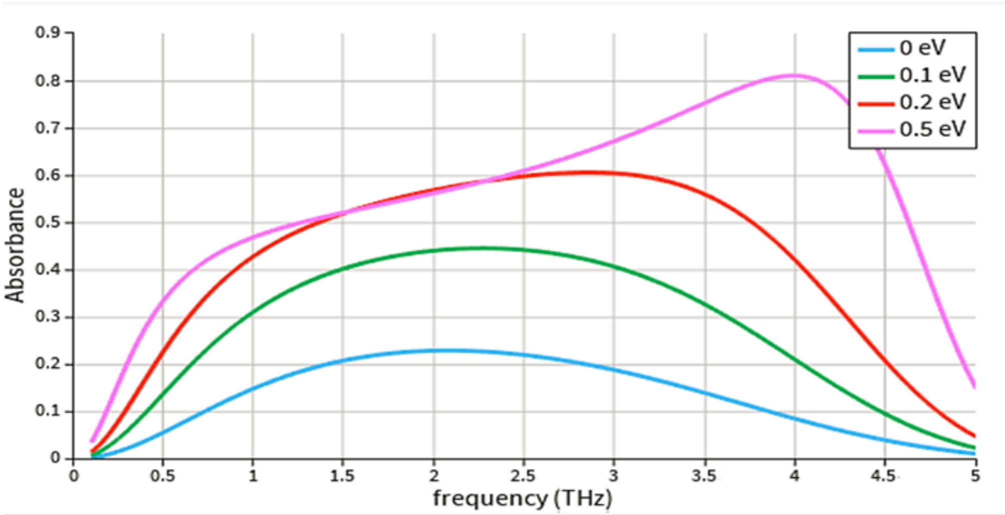


Figure 3.8: variation of absorbance with frequency for different valious the electrical chemical potential [8].

7.2.1 Results

When the geometry of the fishnet metamaterial is changed by adding polygonal objects with index of refraction of 1.53, in addition to A change in the chemical properties of graphene can be achieved by applying a potential difference, where every time we change the value of the chemical potential and observe the rate of absorption with frequency. The change in the potential difference works to control the conductivity of graphene, as the greater the potential difference We notice an increase in the absorption rate, and the reason is due to the increase in the conductivity of graphene, We noticed an improvement in the absorption spectrum and it was wider, and the absorption value reached 80% [8].

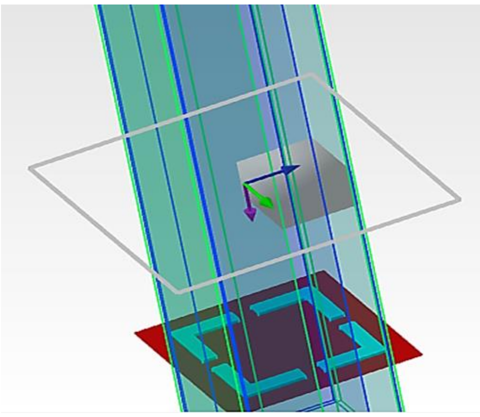
8. The contributions

In addition to re-simulating previous studies carried out by scientists and researchers over the past years, we have chosen the structure of the fishnet design as a good reference in the results of absorption, as a new initiative from us is changing some data and values related to the angles of incidence and polarization of the outgoing radiation. Towards the absorber, as well as causing a change in structure .We were able to record several different results.

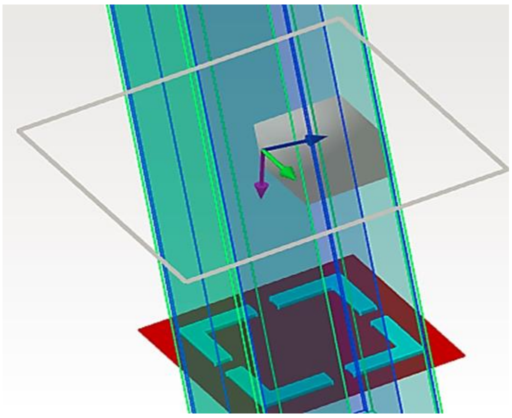
8.1 The first contribution

We changed the characteristics of the radioactive source. The changes were exactly in terms of the incidence angle value. Each time we increased its value and recorded the absorption rate, taking into account that the chemical potential value they fixed, estimated at 0.5ev.

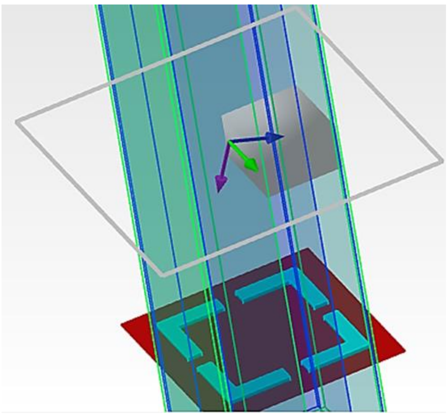
We recorded the results shown in the following figure (3.9; 3.10):



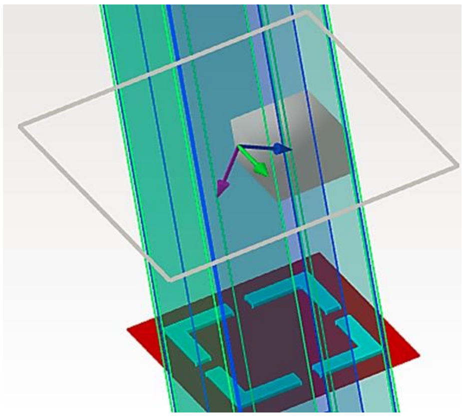
(A)



(B)

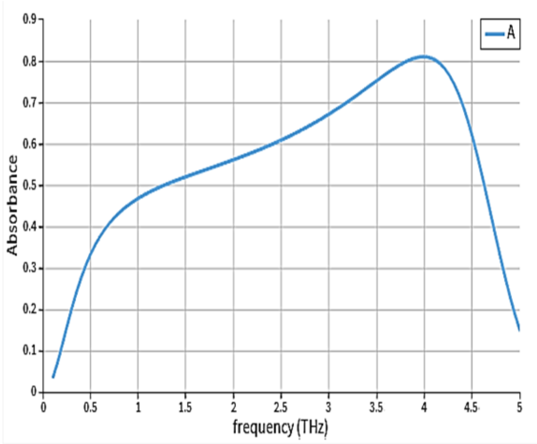


(C)

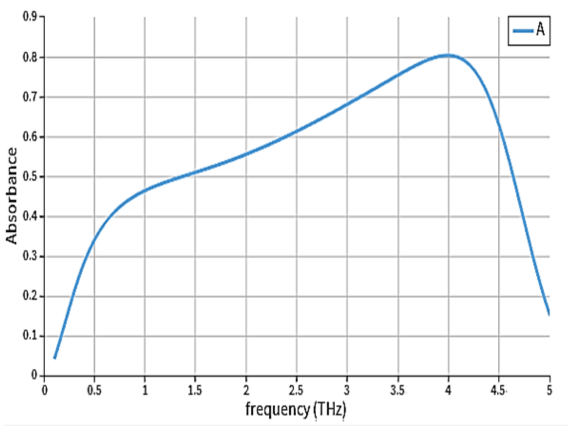


(D)

Figure 3.9: schematic view for different valious the incidence ingle, **(A)** angle theta= 0°, **(B)** angle theta= 10° **, (C)** angle theta = 20° , **(D)** angle theta= 30° **.**



(A)



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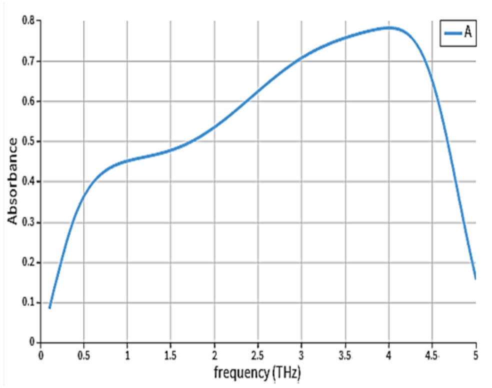

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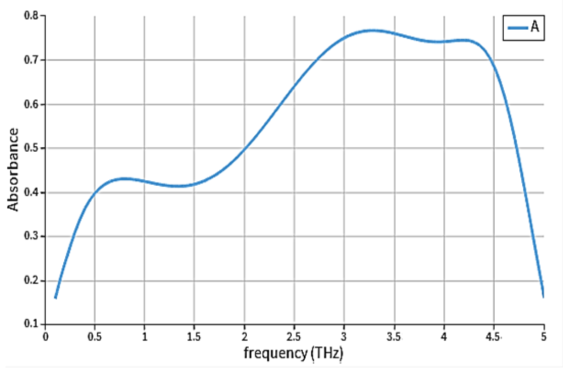


(D)

Figure 3.10: variation of absorbance with frequency for different valious of the incidence angle, **(A)** angle theta= 0° , **(B)** angle theta= 10° **, (C)** angle theta = 20° , **(D)** angle theta= 30° **.**

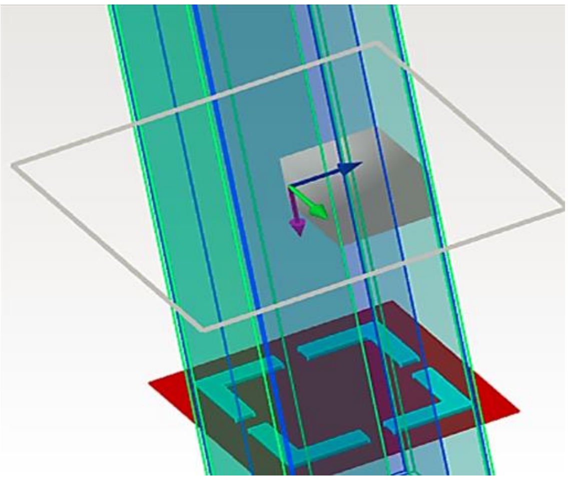
8.1.1 Results

When changing the incidence angle value, we notice that the absorption rate is constant at all values, noting that the chemical potential value they fixed in every case. Therefore, this indicates that the absorber is not sensitive and they not affected when changing the incidence angle, because the absorption rate is constant in all cases and estimated at 80%.

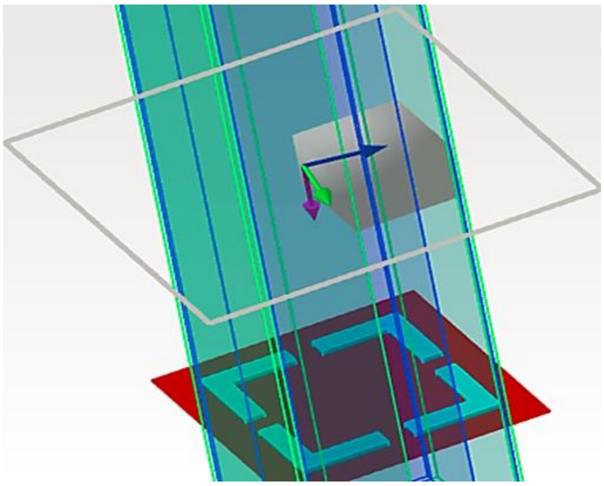
8.2 The second contribution

We changed the characteristics of the radioactive source. The changes were exactly in terms of the Polarization angle value. Each time we increased its value and recorded the absorption rate, taking into account that the chemical potential value they fixed, estimated at 0.5ev.

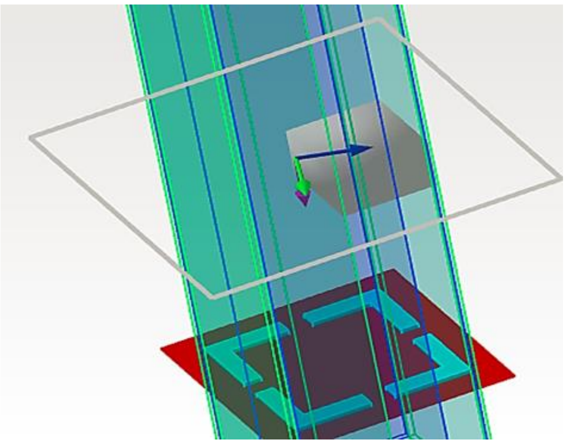
We recorded the results shown in the following figure (3.11, 3.12):



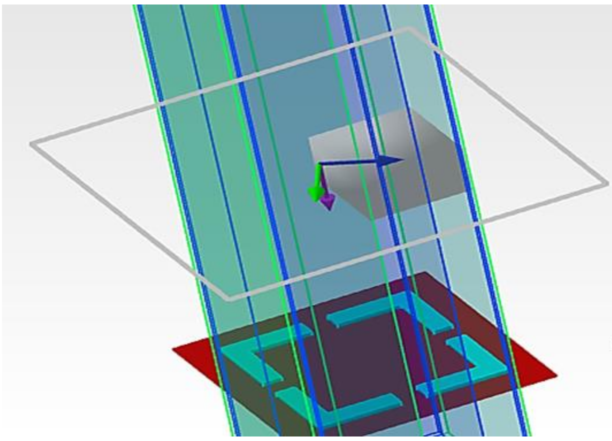
(E)



(F)

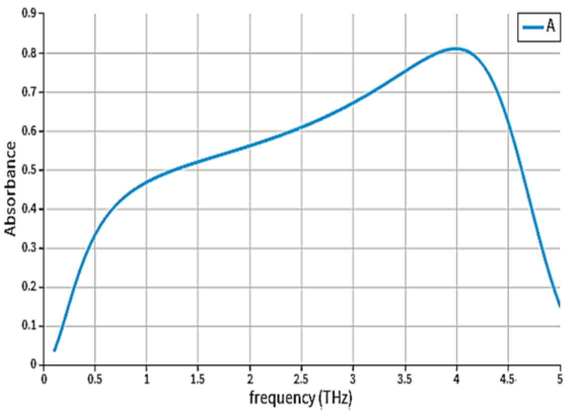


(G)

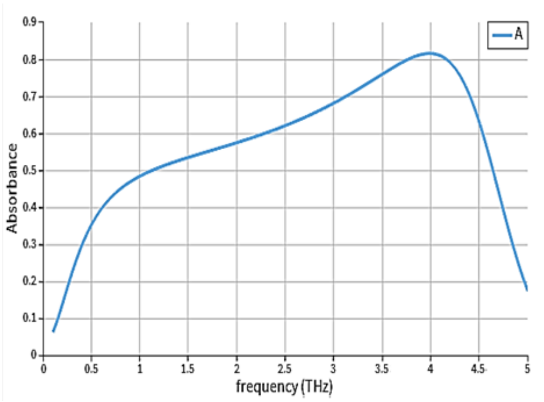


(H)

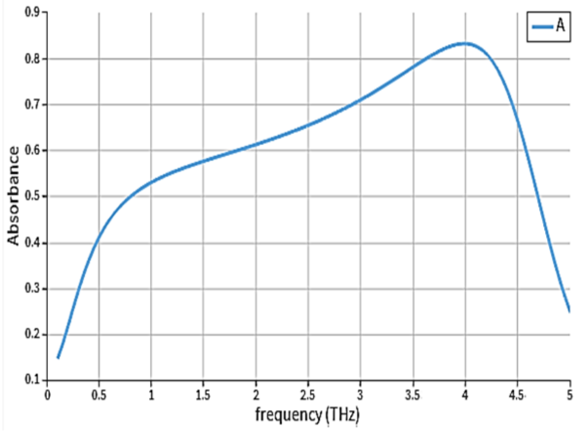
Figure 3.11: schematic view for different valious the Polarization angle, **(E)** angle phi= 90° , **(F)** angle phi= 80° , **(G)** angle phi= 70° , **(H)** angle phi= 60°.

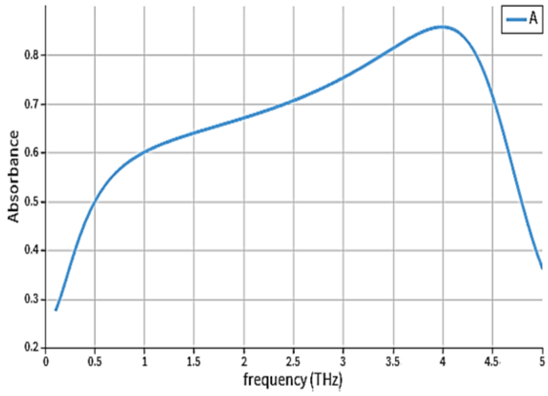


(E)



(F)





(G) **(H)**

Figure 3.12: variation of absorbance with frequency for different valious of the Polarization angle, **(E)** angle phi= 90° , **(F)** angle phi= 80° , **(G)** angle phi= 70° , **(H)** angle phi= 60°.

8.2.1 Results

We notice a slight increase in the absorption value with frequency for different values of the Polarization angle, noting that the value of the chemical potential is constant in each case, as the increase is inversely proportional to the values of the Polarization angle.

In this case, we significantly reduced the value of the Polarization angle down to angle phi= 30° we recorded the results shown in the following figure (3.13, 3.14)

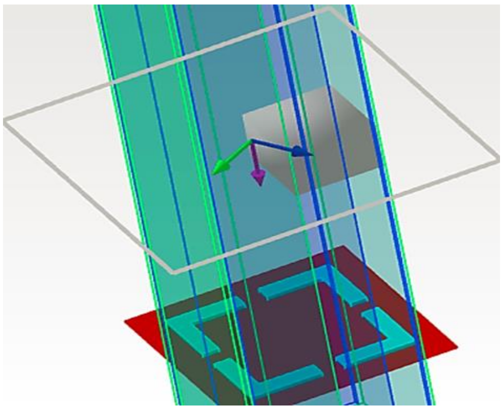


Figure3.13: schematic view for value frequency Of the Polarization, angle theta= 30°**.**

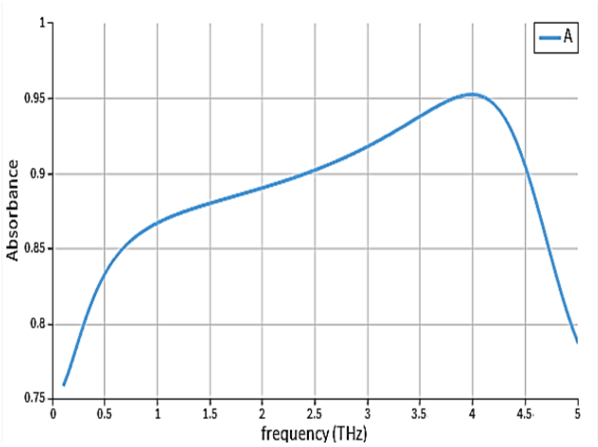


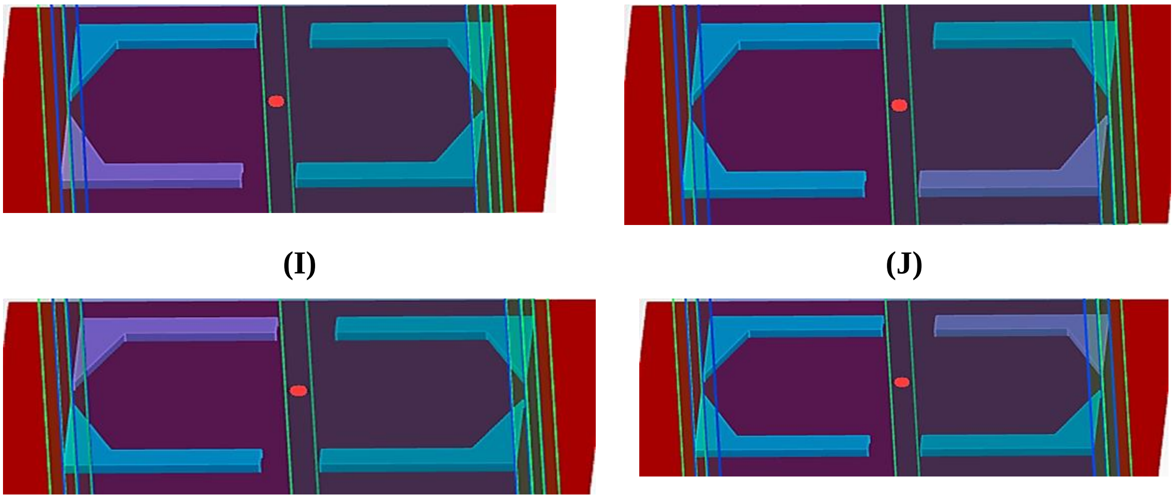
Figure3.14: variation of absorbance with For value Of the Polarization, angle theta30°**.**

8.2.2 Results

We notice that the absorption value increased by a significant percentage with frequency for a different value in the Polarization angle, noting that the value of the chemical potential is constant even in this case, so we conclude that whenever the value of the polarization angle decreases. We record an increase in the absorption percentage, so the absorption is almost perfect, estimated at 95%. This indicates that the absorber is sensitive to changing the polarization angle.

8.3 The third contribution

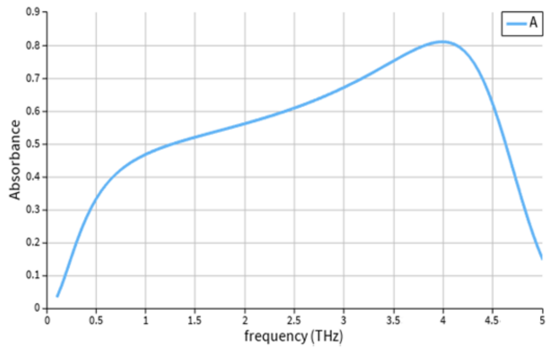
In this part, we changed the structure of the fishing net. It they known that to the geometry of the fishing net, we added polygonal objects with an index of refraction of 1.53. The shape of the four ribs was changed. In addition, we isolated one of the ribs each time. We recorded the results shown in the following figure (3.15, 3.16).



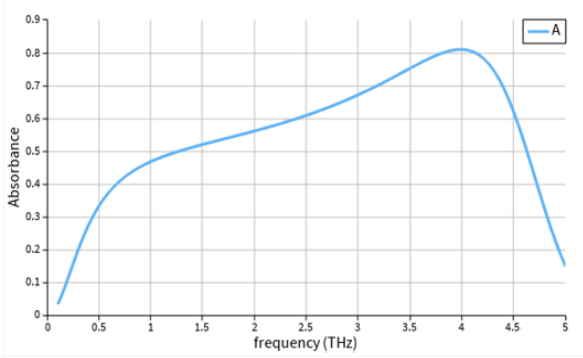
(I) **(J)**

(K) **(L)**

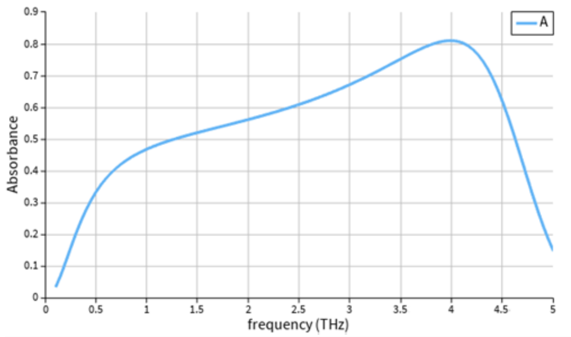
Figure3.15: schematic view of showing a change in fishnet design And isolate one of the polygons.



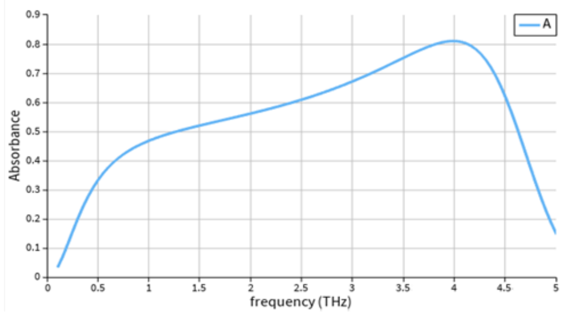
(I)



(J)



(K)



(L)

Figure3.16: variation of absorbance with frequency of showing a change in fishnet design And isolate one of the polygons.

8.3.1 Results

We note that the absorption value is almost constant with frequency when changing the structure of the ribs as well as when isolating each rib, noting that chemical organisms have a fixed value estimated at 0.5ev. We recorded an absorption rate estimated at absorption 80%. This indicates that the absorber is not sensitive. To change the shape of the rib or isolate it.

9. Conclusion

This work aims to study the absorption characteristics of electromagnetic waves within the terahertz spectrum, using an absorber consisting of graphene, which in turn serves as a monolayer of carbon atoms that is highly sought after in various applications due to its intrinsic and excellent electrical properties. In this study, we applied the simulation to uniform design and fishnet. We noticed that the metamaterial fishnet structure produces a broad absorption spectrum and is better than the uniform design.

We also noticed that applying a potential difference to the graphene layer improves the absorption, as the greater the applied potential difference leads to an increase in the conductivity of the graphene, thus we record an increase in the absorption spectrum.

We notice that an absorption value of 80% they recorded at a potential difference of 0.5ev and this they considered a good percentage. In addition, we changed some of the characteristics of the radiation source directed at the absorber, as we changed both the angle of incidence and the angle of polarization. We recorded a stability in the rate of absorption upon a change in the angle of incidence, the value of which they estimated at 80%. We noticed a somewhat significant increase. In the absorption rate when changing the value of the polarization angle, the absorption rate was almost perfect, estimated at 95%. This indicates that the absorber is remarkably sensitive to the polarization angle, unlike the angle of incidence, which is not sensitive to it.

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General Conclusion

General conclusion

In this note, we focused on the physical and chemical mechanisms that can enhance the absorption of electromagnetic radiation, precisely radiation in the terahertz spectrum because it has unique properties that enable it to sweep through all medical, military, and communications fields. In our study, we also focused on the frequency range between 1 and 4 Hz, which lies between the microwave region and the infrared region. In this work, we also provided an overview of the various categories of absorbers, but we focused on the metamaterial absorber category because it has the potential to provide better absorption, and this is due to its different and unique properties, because it they considered synthetic and composite materials, and this is what distinguishes it from natural materials. As stated in our memorandum. We focused on graphene, which they recently discovered in 2004, as this material showed a two-dimensional structure due to its very thin thickness, but it they considered strong and solid due to its strange and promising properties in terms of the physical, optical and mechanical levels. This is what drives the urgent need to use it in Terahertz optical fields. Therefore, we simulated an absorber made of a graphene layer and applied this study to two different designs, namely the uniform design and the fishnet design. In the uniform design, and by applying a potential difference to the graphene layer with different values, we noticed recording an absorption spectrum that was in the form of a double band, but the absorption rate increased when the value of the potential difference increased. Applied. In order to simulate the metamaterial fishnet structure and by applying different potential difference values, as in this case, we changed the design and structure of the fishnet by adding polygonal bodies made of an insulating material with a refractive index of 0.53 on the surface of the graphene. We also recorded an absorption spectrum. More broadly compared to the absorption spectrum recorded in uniform design, where we recorded an absorption rate of 80%, In order to obtain a better absorption spectrum, we supported this simulation with three contributions of our own. These contributions were working on changing some of the characteristics of the fishnet design because it they considered a good reference for absorption, and the changes were exactly at the level of the characteristics of the radiation source. Note that the value of the chemical potential is constant, estimated at 0.5ev. In the first case, we changed the incidence angle values, as we recorded a stability in the absorption value, estimated at 80%.This indicates that the absorber is not sensitive to the incidence angle values. In the second case, we changed the Values of the polarization angle, where we noticed a significant increase in the absorption rate that is inversely proportional to the polarization angle. Therefore, as the polarization angle decreases, we record an increase in the absorption spectrum, as we reached an almost ideal absorption value estimated at 95%. In the third case, we changed the structure of the ribs in addition to Isolation in one of the ribs in a row, noting that the chemical potential are stable even in this case and they estimated at 0.5ev. We recorded a constant absorption rate as well, estimated at 80%. Therefore, this confirms that the absorber is not sensitive to changing the shape of the rib or its isolation. From the results obtained, we conclude that metamaterial absorbers that contain graphene achieve good absorption of electromagnetic waves in the terahertz spectrum, and this they done by applying a difference in chemical potential with high values that work to increase the conductivity of graphene, and this allows for an improvement in the absorption spectrum. Due to the age of technology, there is an urgent need for graphene and its use in all fields with the aim of manufacturing high-quality absorption devices.