METAMATERIAL ABSORBERS AND REFLECTORS FOR MULTIBAND AND WIDEBAND APPLICATIONS

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DEDICATION

This thesis is dedicated to my father Engr. Mustapha Alkali Gajibo, who supported me all through and always stood by my choices and encouraged me as he steers me towards brighter future; To my mothers Hajja Yagana, Hajja Safiya and Hajja Fatimah for contributing in their own ways mostly with endless prayers, comfort and advices; To my siblings, Binta, Awal, Kaka, Hadiza, Ahmed, Kaltum, Muktar, Amina, Nafisa, Yusuf, Halima & Ahmed for their Kind hearts and making me not to feel the distance and the struggle.

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ABSTRACT

Metamaterials (MTMs) are materials artificially engineered by artificially arranging structural elements to achieve unusual properties that do not ordinarily exist in nature. It is no secret that electronic devices and communication devices such as mobile phones, pacemakers, infusion pumps, laptops and others, are becoming even more smaller, precise and sensitive. In addition to that, they tend to move towards higher frequency and are adopting the wireless technology which is susceptible to attenuation and interference. At lower frequencies, antennas are larger, therefore miniaturization is required to enable them fit into those tiny electronic devices. In general, electromagnetic waves propagation is characterized by multiple directions as well as many polarization angles, which contributes to the complexity of the signal at the receiver's end. However, this complexity can be reduced by developing MTM absorbers to absorb any unwanted signals. It can be further reduced by developing MTM reflectors to guide the transmitted signal towards the intended destination. This thesis is aimed at taking advantages of the unusual properties offered by MTMs to develop X-band MTM absorbers and (artificial magnetic conductor) AMC/ MTM reflectors. The new MTM absorbers and MTM reflectors were designed using FR-4 substrate with thickness of 1.6 mm, loss tangent of 0.019 and dielectric constant of 4.6. The MTM absorber catered for the bulky size issues of conventional absorbers and narrow bandwidth issues associated with MTMs absorbers. Whereas the new MTM reflectors catered for the out of phase image current and surface current propagation supported by perfect electric conductor (PEC). Finally, copper wires were used as switches to demonstrate reconfigurability and compactness. The first proposed structure is based on circular ring (CR) structure. It resonated at 11.11 GHz and was modified to have four smaller extended circular rings to demonstrate the concept of size reduction by suppressing the resonance frequency. The second structure is based on the famous "H" pattern absorber, which was modified to have four copper wires as switches in order to manipulate the flow of the circulating charges. A dual-band absorption characteristic with reconfigurability between single band (7.20 GHz) and dual-band (7.20 GHz and 11.20 GHz) absorption was demonstrated. The third structure is made up of four-square patch separated by a vertical bar. The charges flow paths were manipulated by connecting the individual square patch to the vertical bar with copper wires. The concept of connecting multiple neighboring resonances to achieve a wideband absorption was demonstrated. Almost a 100% absorption across the entire X-band region (9.00 GHz to 13.00 GHz) was achieved and furthermore, switchability between total absorbance and total reflection at 11.20 GHz was demonstrated using copper wires. Reflection was more than 75%. The fourth structure is made up of two quad gapped square shaped split-ring resonators (QGSSSRR). This structure also achieved almost 100% absorption across the entire X-band region (9.00 GHz to 13.00 GHz), and it also demonstrated switchability between total absorbance and total reflection at 11.20 GHz. All the proposed designs were tested for incident wave angles (IWAs) in the range of 0^o to 60^o in which almost all of them performed excellently with a minimum absorption rate of close to 80% and reflection rate of close to 75%.

ABSTRAK

Metabahan (MTMs) adalah bahan yang direka secara buatan dengan menyusun unsur struktur tiruan untuk mencapai ciri luar biasa yang biasanya tidak wujud secara semulajadi. Ia bukan rahsia bahawa peranti elektronik dan peranti komunikasi seperti telefon mudah alih, perentak jantung, pam infusi, komputer riba dan lain-lain, menjadi lebih kecil, tepat dan sensitif. Di samping itu, mereka cenderung untuk bergerak ke arah frekuensi yang lebih tinggi dan mengguna pakai teknologi tanpa wayar yang terdedah kepada rosotan dan gangguan. Pada frekuensi yang lebih rendah, antenna adalah lebih besar, oleh itu pengecilan saiz diperlukan untuk membolehkannya dimuatkan ke peranti elektronik kecil itu. Secara umum, perambatan gelombang elektromagnet dicirikan oleh pelbagai arah serta banyak sudut polarisasi yang menyumbang kepada kerumitan isyarat pada akhir penerima. Walau bagaimanapun, kerumitan ini dapat dikurangkan dengan membangunkan penyerap MTM untuk menyerap sebarang isyarat yang tidak diingini. Ia boleh dikurangkan lagi dengan membangunkan pemantul MTM untuk memandu isyarat yang dihantar ke arah destinasi yang dimaksudkan. Tesis ini bertujuan untuk mendapatkan kelebihan sifat luar biasa yang ditawarkan oleh MTM untuk membangunkan penyerap MTM jalur-X dan pemantul AMC / MTM. Penyerap MTM dan pemantul MTM baru direka menggunakan substrat FR-4 dengan ketebalan 1.6 mm, kehilangan tangen 0.019 dan pemalar dielektrik 4.6. Penyerap MTM menampung isu saiz besar penyerap konvensional dan isu jalur lebar sempit yang berkaitan dengan penyerap MTM. Manakala pemantul MTM yang baru disediakan untuk arus imej tidak sefasa dan perambatan arus permukaan yang disokong oleh pengalir elektrik yang sempurna (PEC). Akhirnya, wayar tembaga digunakan sebagai suis untuk menunjukkan kebolehan konfigurasi semula dan kepadatan. Struktur pertama adalah berdasarkan struktur bulatan cincin (CR). Ia menyalun pada frekuensi 11.11 GHz dan telah diubahsuai untuk mempunyai empat lanjutan cincin bulat kecil untuk menunjukkan konsep pengurangan saiz dengan menekan frekuensi resonans. Struktur kedua berdasarkan pada penyerap corak "H" yang telah diubahsuai untuk mempunyai empat wayar tembaga sebagai suis bagi memanipulasi aliran cas bergerak secara bulatan. Ciri penyerapan dwijalur dengan kebolehan konfigurasi semula antara penyerapan satu jalur (7.20 GHz) dan dua jalur (7.20 GHz dan 11.20 GHz). Struktur ketiga terdiri daripada empat tampal segi empat sama yang dipisahkan oleh bar menegak. Laluan aliran cas dimanipulasi dengan menyambung tampal segi empat sama individu ke bar menegak dengan wayar tembaga. Konsep menghubungkan resonans bersebelahan untuk mencapai penyerapan jalur lebar telah ditunjukkan. Hampir 100% penyerapan di seluruh rantau jalur-X (9.00 GHz hingga 13.00 GHz) telah dicapai dan seterusnya, kebolehan berubah antara jumlah penyerapan dan jumlah pantulan pada 11.20 GHz ditunjukkan menggunakan wayar tembaga. Pantulan adalah lebih daripada 75%. Struktur keempat terdiri daripada dua penyalun cincin terpisah berbentuk quad berongga segi empat sama (QGSSSRR). Struktur ini juga mencapai hampir 100% penyerapan merentas seluruh rantau jalur-X (9.00 GHz hingga 13.00 GHz) dan ia juga menunjukkan kebolehan berubah antara jumlah penyerapan dan jumlah pantulan pada 11.11 GHz. Semua reka bentuk yang dicadangkan telah diuji untuk sudut gelombang tuju (IWAs) dalam julat 0^{o} hingga 60^{o} di mana hampir semuanya dilakukan dengan kadar penyerapan minimum menghampiri 80% dan kadar pantulan menghampiri 75%.

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LIST OF ABBREVIATIONS

MTM - Metamaterial

EBG - Electromagnetic Band-Gap

HIS - High Impedance Surface

FSS - Frequency Selective Surface

LHM - Left-Handed Metamaterial

EMW - Electromagnetic Waves

MTMABS - Metamaterial Absorbers

MTMREF - Metamaterial Reflectors

AMC - Artificaial Magnetic Conductor

UTM - University Technology Malaysia

DNG - Double Negative Metamaterial

NIM - Negative Index Materials

BWM - Backward Media

SSR - Split-Ring Resonator

SNG - Sinal To Noise Ratio

CRR - Conductivity of Metal

ELC - Electric Filed Coupled-LC

CELC - Complimentary Electric Field Coupled-LC

OSR - Omega-Shaped Resonator

PBG - Photonic Bandgap

FWHM - Full Width At Half Maximum

IWA - Incident Wave Angle

MNG - Mu-Negative

ENG - Epsilon Negative

DSP - Double Positive

LIST OF SYMBOLS

E - Electric Field
H - Magnetic Field
ε - Permittivity
μ - Permeability
ε_r - Relative Permittivity
μ_r - Relative Permeability
n - Refractive Index
c - Speed of Light
ω - Radian Frequency
ω_p - Plasma Radian Frequency
k - Complex wavenumber
f - Frequency
λ - Wavelength
Z - Impedence
β - Propagation Constant
σ - Conductivity of Metal
η - Wave Impedance

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CHAPTER 1

INTRODUCTION

1.1 Introduction

Metamaterials (MTMs) are structures engineered artificially to exhibit extraordinary properties such as negative refractive index [1, 2], negative permeability and negative permittivity (artificial magnetism) [3, 4] which are not found in nature. One unique thing about MTMs is that they do not derive their properties from the original materials but rather from the newly designed structures. Veselago first envisaged the concept of MTM in 1963 [5] which was later validated by Pendry and Smith. MTMs are designed using periodic elements based on equivalent lumped circuits consisting of inductors and capacitors. The equivalent lump element circuit determines the resonance frequency and the dimensions of the lump elements are much smaller than that of operating wavelength [6].

MTMs, based on their characteristics are divided into various categories which include artificial magnetic conductor (AMC) structures, electromagnetic bandgap (EBG), high impedance surface (HIS), Frequency selective surface (FSS), photonic crystal, left-handed metamaterials (LHM), etc. These categories have their own unique properties which are applicable to the development or enhancement of various electromagnetic devices.

1.2 Background Study

What are Electromagnetic waves (EMW) absorbers and EMW reflectors? It is worth mentioning that both are products of FSS, though some absorbers are realized by modifying some HIS. In details;

EMW absorbers are structures that can absorber incidental electromagnetic waves. They are designed to minimize reflection and transmission by maximizing energy loss within the structure. Other than the conventional electromagnetic absorber, other absorbers such as the Jaumann absorber [7-11], Salisbury screen [12-14], crossed grating absorbers [15, 16], Dallenbach layer [17, 18] and circuit analogue (CA) absorbers [19-22] are in existence, but they all have their various drawbacks. For instance, the Jaumann absorber and the Salisbury both use the concept of incidental electromagnetic waves cancellation. The Jaumann absorber came to existence due to the disadvantage of absorbing frequency associated with the Salisbury absorber as it operates at a quarter wavelength. It is worth noting that the Jaumann absorber offers only a single and narrow frequency band absorption. In addition to that also, both the Jaumann and Salisbury absorbers are thick in other to enable them to absorb electromagnetic waves of different frequencies. [23]

EMW reflectors are sometimes called Artificial magnetic conductors (AMC)s. These are structures purposely designed with unusual boundary conditions. These boundaries conditions were made in such a way that the structure will be selective in supporting surface wave currents [24]. Initially, conventional metallic conductors and perfect electric conductor (PEC) were often used for antenna ground planes. These were limited by their drawbacks, which includes reversal or out of phase image currents and propagation of surface current, which is radiation caused by an infinite ground plane. AMCs counter these drawbacks and even exhibits the ability to reduce back-radiation as well as increase gain. [25].

It is undeniable that MTM has offered more advantages than disadvantages, especially in the fields of electromagnetic structures. Therefore, researchers are at their heels, exploring all the benefits it offers. One of the areas in which researchers are focused on is the use of MTM structures for absorbers and reflectors. MTM structures will not only address the substrate thickness problem in the previous absorbers, but instead it will even advance further to enhance them in terms of portability and compactness as well as entitle them to the freedom of design structures (not fixed to quarter wavelength).

1.3 Problem statement

With advancement in technology, electronic devices and communication devices such as pacemakers, infusion pumps, mobile phones, laptops and others as mentioned in [26, 27] [28], are becoming even more smaller, precise and even more sensitive [29, 30]. In addition to that also, they tend to move towards higher frequency and are adopting the wireless technology [31]. At lower frequencies, antennas are larger, therefore miniaturization is required to enable them fit into those tiny electronic devices while at higher frequencies, one of the prevalence challenges is the ability to receive a substantial amount of the transmitted signal at the receiver. These challenges are caused by so many different factors. Amongst these factors are, interference caused by unwanted signals in the surroundings, the reflection of the transmitted signals by the surrounding elements [32]. The interference causes a rise in signal to noise ratio (SNR) which leads to high error rate or total loss of data whereas the reflection causes scattering, which results in multipath.

However, this interference can be reduced if not eliminated by developing multiband or wideband MTM absorbers (MTMAbs) to absorb any unwanted surroundings electromagnetic waves [33] [34]. On the other hand, developing a MTM reflector (MTMRef) and placing it at a desired position can help in reducing the scattering or multipath caused by far distance surround elements [35]. With this two in place, interference will be reduced, and the signal be guided to the targeted destination, which will ensure the reception of ample amount of the transmitted signal.

It is worth noting that multiband MTMAbs can absorb the unwanted electromagnetic waves for selected bands of operations with windows in-between. While the wideband MTMAbs can absorb can for a wider band without windows in-between. In general, MTMAbs are capable of intercepting electromagnetic waves radiated daily by home appliances, cell phones, Wi-Fi, etc. which tends to be harmful to human and animals. Whereas MTMRefs are capable of improving gains when combined with other antennas. Besides, both combined interchangeably can provide enhanced stealth mode to avoid radar detection or reveal for warships, fighter jets, and tanks.

1.4 Research objectives

The objectives of this project are:

i. To study, understand MTMAbs and MTMRefs.
ii. To design MTMAbs and MTMRef structures for X-band applications.
iii. To fabricate the designed structures.
iv. To measure and characterise the results in anechoic chamber.

In essence, to design, simulate, fabricate, measure and analyze both the MTMAbs and the MTMRef. The proposed EMW MTMAbs and the MTMRef should be able reduce interference, and increase directivity of transmitted electromagnetic waves as well as demonstrate compactness when compared with the conventional absorbers. Also, the new structures should be to adapt to new surroundings/ environment and should be able to switch between total absorbance and total reflectance using copper wires as switches.

1.5 Scope of Work

The scope of this research includes using basic design concept for metamaterial absorber, and reflectors learned from literature review. Furthermore, it is limited to the availability of facilities and resources required for achieving the objectives of the research.

First, an in-depth literature review was conducted to know the theoretical aspect, have a better understanding of both metamaterial absorbers and metamaterial reflectors as well as reconfigurable/ tunable structures from books, journals, conferences, and academicals or industrial research.

The obtained knowledge of the ideology, the concept, and formulas of electromagnetic structures were used to calculate reference point parameters. These parameters were then designed using CST and then optimized the structure for better results.

The optimized designs were fabricated using FR4 fire Retardant-4 substrates. Due to the nature of the structure's size and the designed frequency range, fabrication within the UTM facility was quite impossible. Therefore, it was outsourced to a company named "Jac Engineering".

Finally, the fabricated structures were measured in the anechoic chamber, and the results were compared with the simulated results.

1.6 Thesis Outline

Chapter 1 introduces the EMW from absorber and reflector's perspectives, an overview of the research work, problem statements, objectives and scope of the project.

Chapter 2 gives an overview of MTMs and basic intro to left-Handed Metamaterial (LHM), resonant elements and electromagnetic band gap (EBG). Absorption theories of metamaterial absorbers (MTMAbs) and reflection theories of AMC/metamaterial reflectors were discussed. Previous works related to MTMAbs and MTM reflectors were reviewed and summarized.

Chapter 3 gives insight on design specifications, emphasis and details out research methodology and the flow of the research work. It further gives step by step guide to simulation setup, basic equations for MTMAbs and MTMRefs. The last part involves the fabrications of prototypes structures as well as measurement process flow.

Chapter 4 describes the design process for Circular Ring and Split Ring Resonator MTMAbs. In this chapter, new designs of MTMAbs were presented, and their performance in terms of absorption and polarization were discussed. These designs were divided into three categories, namely single band MTM Absorber, dual/multiband MTM Absorber and wideband MTM Absorber. In addition to that, other parametric studies were conducted and reported.

Chapter 5 is divided into two sections; section one introduces a few new designs of MTMRefs based on resonant element “square patch”, it also presented their performances in terms of reflection, reflection phase, and polarizations. While section two adapted a few designs from chapter 4 and 5 and demonstrated switchability using copper wires. The structures were capable of switching between total absorption and total reflection. Their performances were tested based on absorption and reflection capabilities.

Chapter 6 concludes the thesis and gives recommendations and suggestions for future work.

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Appendix A: LIST OF PUBLICATIONS

- **Journal Papers:**

- M. Gajibo, M. K. A. Rahim, N. Murad, O. Ayop, H. Majid, D. Raimi " Entire X-band region metamaterial absorber and reflector with a microstrip patch switch for X-band application," *Indonesian Journal of Electrical Engineering and Computer Science*, vol. 15, no. 3 , p. 35~29, 03/09/2019
- M. Gajibo, M. K. A Rahim, N. Murad, O. Ayop, and H. Majid, "Switchable Wideband Metamaterial Absorber and AMC reflector for X-band Applications and Operations," *Telkomnika (Telecommunication Computing Electronics and Control)*, vol. 16, pp. 1535-1541, 08/01 2018
- M. Gajibo, M. K. A. Rahim, N. Murad, O. Ayop, B. Bala, and H. Majid, "X-band Operations Metamaterial Absorber with Extended Circular Ring Topology for Size Reduction," *Indonesian Journal of Electrical Engineering and Computer Science*, vol. 6, p. 180, 04/01 2017

- **Conferences Papers:**
  - *International Conference on Electrical, Electronic, Communication and Control Engineering (ICEECC) 28th – 30th November, 2018, Johor Bahru, Malaysia.*
    - Entire X-band Region Metamaterial Absorber and Reflector with a Microstrip Patch Switch for X-band Applications
  - *IEEE Asia Pacific Microwave Conference (APMC) 13th - 16th November, 2018, Kuala Lumpur, Malaysia.*
    - A Single and dual band selectable MTM absorber or Reflector
  - *International Symposium on Antennas and Propagation (ISAP) 23rd - 26th October 2018, Busan, Korea.*
    - X-Band Directivity Improvement Using Reflector
  - *Regional Conference on Electrical and Electronics Engineering (RCEEE), 14th to 15th August, 2018, Pulau Pinang, Malaysia.*
    - Switchable X-band Reflector/ Wideband Absorber
  - *International Conference on Electrical, Electronic, Communication and Control Engineering (ICEECC) 5th – 6th December, 2017, Kuala Lumpur, Malaysia.*
    - Switchable Wideband Metamaterial Absorber and AMC reflector for X-band Applications and Operations
  - *International Symposium on Antennas and Propagation (ISAP) 30th Oct. – 2nd Nov. 2017, Phuket, Thailand.*
    - *S*ingle / Dual Band selectable MTM Absorber
  - *META 2017, International Conference on Metamaterials, Photonic Crystals and Plasmonics, 25th – 28th, July, 2017, Incheon - Seoul, South Korea.*

    - 9.5GHz MTM Reflector for X-band applications and operations.

- *International Conference on Electrical, Electronic, Communication and Control Engineering (ICEECC) 18th – 19th December, 2016, Johor Bharu, Malaysia.*
    - X-band Operations Metamaterial Absorber with Circular Rings for Size Reduction

- *META 2016, International Conference on Metamaterials, Photonic Crystals and Plasmonics, 25th – 28th, July, 2016, Torremolinos (Malaga), Spain.*
    - Switchable Metamaterial Absorber/ Reflector for X-band Applications operating at 10.7GHz.

- *IEEE Asia-Pacific Conference on Applied Electromagnetics (APACE) 8 - 10 December, 2014 at Johor Bahru, Johor, Malaysia.*
    - Frequency Reconfigurable Epsilon Negative Metamaterial Antenna.