

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 (QGSSRR). 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° to 60° 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 (QGSSRR). 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° hingga 60° 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	-	Artificial Magnetic Conductor
UTM	-	University Technology Malaysia
DNG	-	Double Negative Metamaterial
NIM	-	Negative Index Materials
BWM	-	Backward Media
SSR	-	Split-Ring Resonator
SNG	-	Signal To Noise Ratio
CRR	-	Conductivity of Metal
ELC	-	Electric Field Coupled-LC
CELC	-	Complementary 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	-	Impedance
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 absorb 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 order to enable them to absorb electromagnetic waves of different frequencies. [23]

EMW reflectors are sometimes called Artificial magnetic conductors (AMCs). These are structures purposely designed with unusual boundary conditions. These boundary 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 academics 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.

REFERENCES

- [1] D. R. Smith, J. B. Pendry, and M. C. Wiltshire, "Metamaterials and negative refractive index," *Science*, vol. 305, no. 5685, pp. 788-792, 2004.
- [2] F. Bilotti and L. Sevgi, "Metamaterials: Definitions, properties, applications, and FDTD-based modeling and simulation," *International Journal of RF and Microwave Computer-Aided Engineering*, vol. 22, no. 4, pp. 422-438, 2012.
- [3] D. R. Smith, W. J. Padilla, D. Vier, S. C. Nemat-Nasser, and S. Schultz, "Composite medium with simultaneously negative permeability and permittivity," *Physical review letters*, vol. 84, no. 18, p. 4184, 2000.
- [4] V. G. Veselago, "THE ELECTRODYNAMICS OF SUBSTANCES WITH SIMULTANEOUSLY NEGATIVE VALUES OF ϵ AND μ ," *Soviet Physics Uspekhi*, vol. 10, no. 4, pp. 509-514, 1968/04/30 1968, doi: 10.1070/pu1968v010n04abeh003699.
- [5] V. Veselago, "The electrodynamic properties of a mixture of electric and magnetic charges," *Soviet Physics JETP*, vol. 25, no. 4, 1967.
- [6] F. Bilotti, A. Toscano, L. Vegni, K. Aydin, K. B. Alici, and E. Ozbay, "Equivalent-Circuit Models for the Design of Metamaterials Based on Artificial Magnetic Inclusions," *IEEE Transactions on Microwave Theory and Techniques*, vol. 55, no. 12, pp. 2865-2873, 2007, doi: 10.1109/TMTT.2007.909611.
- [7] M. Hyde, A. E. Bogle, and M. Havrilla, "Nondestructive characterization of Salisbury screen and Jaumann absorbers using a clamped rectangular waveguide geometry," *Measurement*, vol. 53, 07/01 2014, doi: 10.1016/j.measurement.2014.03.025.
- [8] L. J. du Toit and J. H. Cloete, *Advances in the design of Jaumann absorbers*. 1990, pp. 1212-1215 vol.3.
- [9] L. Ke, Z. Xin, H. Xinyu, and Z. Peng, "Analysis and design of multilayer Jaumann absorbers," 05/01 2011, doi: 10.1109/ICMTCE.2011.5915168.
- [10] M. A. Ramkumar and C. Sudhendra, "Novel Ultra Wide Band Polarisation Independent Capacitive Jaumann Radar Absorber," *Defence Science Journal*, vol. 68, p. 64, 12/18 2017, doi: 10.14429/dsj.68.12025.
- [11] J. R. Nortier, C. A. Van der Neut, and D. E. Baker, "TABLES FOR THE DESIGN OF JAUMANN MICROWAVE ABSORBER," vol. 30, pp. 219-222, 09/01 1987.
- [12] R. L. Fante and M. T. McCormack, "Reflection properties of Salisbury screen," *Antennas and Propagation, IEEE Transactions on*, vol. 36, pp. 1443-1454, 11/01 1988, doi: 10.1109/8.8632.
- [13] Z. Zhou, K. Chen, J. Zhao, Y. Feng, and Y. Li, *Expanding Microwave Absorption Bandwidth with Metasurface Salisbury Screen*. 2018, pp. 440 (4 pp.)-440 (4 pp.).
- [14] F. Che Seman, R. Cahill, and V. F. Fusco, "Salisbury screen with reduced angular sensitivity," *Electronics Letters*, vol. 45, pp. 147-149, 03/01 2009, doi: 10.1049/el:20092811.
- [15] X. Mao and L. Zeng, "Design and fabrication of crossed gratings with multiple zero-reference marks for planar encoders," *Measurement Science and Technology*, vol. 29, 11/27 2017, doi: 10.1088/1361-6501/aa9d5e.

- [16] E. Popov, D. Maystre, R. McPhedran, M. Nevière, M. C Hutley, and G. H Derrick, "Total absorption of unpolarized light by crossed gratings," *Optics express*, vol. 16, pp. 6146-55, 05/01 2008, doi: 10.1364/OE.16.006146.
- [17] F. Li, P. Chen, Y. Poo, and R.-X. Wu, *Achieving Perfect Absorption by the Combination of Dallenbach Layer and Salisbury Screen*. 2018, pp. 1507-1509.
- [18] D. L. Jaggard, N. Engheta, and J. Liu, "Chiroshield: A Salisbury/Dallenbach Shield Alternative," *Electronics Letters*, vol. 26, pp. 1332-1334, 09/16 1990, doi: 10.1049/el:19900859.
- [19] B. A. Munk, P. Munk, and J. Pryor, "On Designing Jaumann and Circuit Analog Absorbers (CA Absorbers) for Oblique Angle of Incidence," *Antennas and Propagation, IEEE Transactions on*, vol. 55, pp. 186-193, 02/01 2007, doi: 10.1109/TAP.2006.888395.
- [20] E. J. Riley, E. Lenzing, and R. Narayanan, "X-Band Circuit-Analog Absorbers using Unidirectional Carbon-Fiber Laminas," *IEEE Antennas and Wireless Propagation Letters*, vol. PP, pp. 1-1, 04/30 2018, doi: 10.1109/LAWP.2018.2831909.
- [21] L. M. V. Abdulhakim and A. C K, "A Novel Polarization Independent Wideband Circuit Analog Absorber Using Crossed Loops," *Radioengineering*, vol. 27, pp. 738-745, 09/14 2018, doi: 10.13164/re.2018.0738.
- [22] B. A. Munk, "Jaumann and Circuit Analog Absorbers," 2005, pp. 315-335.
- [23] C. M. Watts, X. Liu, and W. J. Padilla, "Metamaterial electromagnetic wave absorbers," *Advanced materials*, vol. 24, no. 23, pp. OP98-OP120, 2012.
- [24] M. Hiranandani, A. Yakovlev, and A. Kishk, "Artificial magnetic conductors realised by frequency-selective surfaces on a grounded dielectric slab for antenna applications," *IEE Proceedings-Microwaves, antennas and propagation*, vol. 153, no. 5, pp. 487-493, 2006.
- [25] B. Zhu, Y. Feng, J. Zhao, C. Huang, and T. Jiang, "Switchable metamaterial reflector/absorber for different polarized electromagnetic waves," *Applied Physics Letters*, vol. 97, no. 5, p. 051906, 2010.
- [26] N. Badizadegan, S. Greenberg, H. Lawrence, and K. Badizadegan, "Radiofrequency Interference in the Clinical Laboratory: Case Report and Review of the Literature," *American journal of clinical pathology*, vol. 151, 01/21 2019, doi: 10.1093/ajcp/aqy174.
- [27] E. Vagdatli, V. Konstandinidou, N. Adrianakis, I. Tsikopoulos, A. Tsikopoulos, and K. Mitsopoulou, "Effects of Electromagnetic Fields on Automated Blood Cell Measurements," *Journal of laboratory automation*, vol. 19, 01/24 2014, doi: 10.1177/2211068213520492.
- [28] R. Togt, E. Lieshout, R. Hensbroek, E. Beinat, J. Binnekade, and P. Bakker, "Electromagnetic Interference From Radio Frequency Identification Inducing Potentially Hazardous Incidents in Critical Care Medical Equipment," *JAMA : the journal of the American Medical Association*, vol. 299, pp. 2884-90, 06/01 2008, doi: 10.1001/jama.299.24.2884.
- [29] L. Goldberg, "When is a medical device not a medical device?," vol. 285, 08/24 2010.
- [30] A. Louis, "Powering miniaturized medical devices: Advanced lithium battery chemistries enable self-powered medical devices to become smaller while delivering uncompromised performance," vol. 57, 08/01 2015.
- [31] D. Kissinger and J. C. Chiao, "Medical Applications of Radio-Frequency and Microwaves-Sensing, Monitoring, and Diagnostics [From the Guest Editors'

- Desk]," *Microwave Magazine, IEEE*, vol. 16, pp. 34-38, 05/01 2015, doi: 10.1109/MMM.2015.2398593.
- [32] M. Fujii, "A new mode of radio wave diffraction via the terrestrial surface plasmon on mountain range: TERRESTRIAL SURFACE PLASMON," *Radio Science*, vol. 51, 08/01 2016, doi: 10.1002/2016RS006068.
- [33] L. Hualiang, Y. Guo, G. Ji, Y. Zhao, and Z. Xu, "Interface Polarization Strategy to Solve Electromagnetic Wave Interference Issue," *ACS Applied Materials & Interfaces*, vol. 9, 01/24 2017, doi: 10.1021/acsami.6b16223.
- [34] J. Chiappe, "Additional techniques to reduce heatsink emissions utilizing RF absorbers," in *2012 IEEE International Symposium on Electromagnetic Compatibility*, 6-10 Aug. 2012, pp. 56-63, doi: 10.1109/IEMC.2012.6351750.
- [35] X. Begaud, A. Lepage, S. Varault, M. Soiron, and A. Barka, "Ultra-Wideband and Wide-Angle Microwave Metamaterial Absorber," *Materials*, vol. 11, p. 2045, 10/20 2018, doi: 10.3390/ma11102045.
- [36] A. Lakhtakia, W. S. Weiglhofer, and I. J. Hodgkinson, "Complex mediums II: Beyond linear isotropic dielectrics," in *Complex Mediums II: Beyond Linear Isotropic Dielectrics*, 2001, vol. 4467.
- [37] A. Sihvola, "Metamaterials in electromagnetics," *Metamaterials*, vol. 1, no. 1, pp. 2-11, 2007.
- [38] A. Sihvola, "Metamaterials: A Personal View," *Radioengineering*, vol. 18, no. 2, 2009.
- [39] M. Lapine and S. Tretyakov, "Contemporary notes on metamaterials," *IET microwaves, antennas & propagation*, vol. 1, no. 1, pp. 3-11, 2007.
- [40] Y. J. Kim, Y. J. Yoo, J. S. Hwang, and Y. P. Lee, "Ultra-broadband microwave metamaterial absorber based on resistive sheets," *Journal of Optics*, vol. 19, no. 1, p. 015103, 2016/12/09 2016, doi: 10.1088/2040-8986/19/1/015103.
- [41] S. Islam Sikder, R. Iqbal Faruque Mohammad, and T. Islam Mohammad, "Design and absorption analysis of a new multiband split-S-shaped metamaterial," in *Science and Engineering of Composite Materials* vol. 24, ed, 2017, p. 139.
- [42] M. J. Hossain, M. R. I. Faruque, and M. T. Islam, "Design and analysis of a new composite double negative metamaterial for multi-band communication," *Current Applied Physics*, vol. 17, no. 7, pp. 931-939, 2017/07/01/ 2017, doi: <https://doi.org/10.1016/j.cap.2017.04.008>.
- [43] H. Chen, B. I. Wu, and J. A. Kong, "Review of Electromagnetic Theory in Left-handed Materials," *Journal of Electromagnetic Waves and Applications*, vol. 20, no. 15, pp. 2137-2151, 2006/01/01 2006, doi: 10.1163/156939306779322585.
- [44] V. Veselago, L. Braginsky, V. Shklover, and C. Hafner, *Negative Refractive Index Materials*. 2006, pp. 189-218.
- [45] S. N. Burokur, M. Latrach, and S. Toutain, "Analysis and Design of Waveguides Loaded with Split-Ring Resonators," *Journal of Electromagnetic Waves and Applications*, vol. 19, no. 10, pp. 1407-1421, 2005/01/01 2005, doi: 10.1163/156939305775525864.
- [46] C. Chan, J. Li, and K. H. Fung, "On extending the concept of double negativity to acoustic waves," *Journal of Zhejiang University SCIENCE A*, vol. 7, pp. 24-28, 01/01 2006, doi: 10.1631/jzus.2006.A0024.
- [47] S. Islam, M. R. Faruque, M. Islam, and T. Alam, *A new mu-negative metamaterial*. 2015.

- [48] S.-Y. Chen, R. Ouedraogo, A. Temme, A. Diaz, and E. Rothwell, *MNG-metamaterial-based efficient small loop antenna*. 2009, pp. 1-4.
- [49] H. Kondori, M. Mansouri-Birjandi, and S. Tavakoli, "Effects of an MNG metamaterial on a microstrip patch antenna," *International Journal on Communications Antenna and Propagation*, vol. 2, 06/01 2012.
- [50] L. Guo, "A high-gain and frequency-tunable bow tie antenna with epsilon-negative metasurface," *Journal of Electromagnetic Waves and Applications*, vol. 29, pp. 693-702, 07/31 2018.
- [51] M. Gajibo, M. K. A. Rahim, B. Bala, and H. Majid, "Reconfigurable epsilon negative metamaterial antenna," pp. 265-267, 02/17 2015, doi: 10.1109/APACE.2014.7043797.
- [52] I. A. Buriak, V. O. Zhurba, G. S. Vorobjov, V. R. Kulizhko, O. K. Kononov, and O. Rybalko, "Metamaterials: Theory, Classification and Application Strategies (Review)," *Journal of Nano- and Electronic Physics*, vol. 8, pp. 04088-1, 12/01 2016, doi: 10.21272/jnep.8(4(2)).04088.
- [53] K. Y. e. Bliokh and Y. P. Bliokh, "What are the left-handed media and what is interesting about them?," *Physics-Uspexhi*, vol. 47, no. 4, pp. 393-400, 2004.
- [54] J. B. Pendry, A. Holden, W. Stewart, and I. Youngs, "Extremely low frequency plasmons in metallic mesostructures," *Physical review letters*, vol. 76, no. 25, p. 4773, 1996.
- [55] R. A. Shelby, D. R. Smith, and S. Schultz, "Experimental verification of a negative index of refraction," *science*, vol. 292, no. 5514, pp. 77-79, 2001.
- [56] C. Parazzoli, R. Gregor, K. Li, B. Koltenbah, and M. Tanielian, "Experimental verification and simulation of negative index of refraction using Snell's law," *Physical Review Letters*, vol. 90, no. 10, p. 107401, 2003.
- [57] R. A. Shelby, D. R. Smith, S. Nemat-Nasser, and S. Schultz, "Microwave transmission through a two-dimensional, isotropic, left-handed metamaterial," *Applied Physics Letters*, vol. 78, pp. 489-491, 01/22 2001, doi: 10.1063/1.1343489.
- [58] C. Caloz and T. Itoh, *Electromagnetic metamaterials: transmission line theory and microwave applications*. John Wiley & Sons, 2005.
- [59] N. Engheta and R. W. Ziolkowski, *Metamaterials: physics and engineering explorations*. John Wiley & Sons, 2006.
- [60] R. A. Shelby, D. R. Smith, and S. Schultz, "Experimental verification of negative index of refraction," *Science*, vol. 292, 01/01 2001.
- [61] V. Sharma, S. Pattnaik, T. Garg, and S. Devi, "A microstrip metamaterial split ring resonator," *International Journal of the Physical Sciences*, vol. 6, pp. 660-663, 01/18 2011.
- [62] H. Imtiaz, T. Ejaz, T. Zaidi, and Z. Nisha Khan, *Design And Analysis Of Dual Split Ring Resonator*. 2019.
- [63] S. Llewellyn Smith and A. M. J. Davis, "The split ring resonator," *Proceedings of The Royal Society A: Mathematical, Physical and Engineering Sciences*, vol. 466, 09/27 2010, doi: 10.1098/rspa.2010.0047.
- [64] M. Yoo and S. Lim, "Switchable Electromagnetic Reflector/Absorber with Electric-Field-Coupled LC Resonator," *Electromagnetics*, vol. 34, 06/16 2014, doi: 10.1080/02726343.2014.910375.
- [65] B. Bala, M. K. A. Rahim, N. Murad, and M. H Mokhtar, "Compact Triple Band Metamaterial Antenna Based on Modified Electric- field Coupled-LC Resonator," *Jurnal Teknologi*, vol. 701, pp. 2180-3722, 08/01 2014, doi: 10.11113/jt.v70.2914.

- [66] B. Bala, M. K. A. Rahim, and N. Murad, "Small electrical metamaterial antenna based on coupled electric field resonator with enhanced bandwidth," *Electronics Letters*, vol. 50, pp. 138-139, 01/30 2014, doi: 10.1049/el.2013.3884.
- [67] D. Pal, V. Jindal, A. K. Bandyopadhyay, L. Kumar Verma, and R. Singhal, *Performance enhancement of coupled-fed printed log-periodic antenna using complimentary split ring resonator*. 2017, pp. 2817-2821.
- [68] P. Garg and P. Jain, "Design and Analysis of Complimentary Split Ring Resonator Backed Microstrip Transmission Line Using Equivalent Circuit Model," *Journal of Communications Technology and Electronics*, vol. 63, pp. 1424-1430, 12/01 2018, doi: 10.1134/S1064226918120069.
- [69] T. H. Hand, J. Gollub, S. Sajuyigbe, D. Smith, and S. Cummer, "Characterization of complementary electric field coupled resonant surface," *Applied Physics Letters*, vol. 93, pp. 212504-212504, 12/01 2008, doi: 10.1063/1.3037215.
- [70] Y. Torabi, G. Dadashzadeh, and H. Oraizi, "Miniaturized sharp band-pass filter based on complementary electric-LC resonator," *Applied Physics A*, vol. 122, 04/01 2016, doi: 10.1007/s00339-016-9787-2.
- [71] 刘. Liu Yao and 陈. Chen Yuegang, "Resonance of I-Shaped Metamaterials," *Acta Optica Sinica*, vol. 38, p. 0324001, 03/10 2018, doi: 10.3788/AOS201838.0324001.
- [72] Y. Sun, Z. Du, J. Du, Y. Liu, and M. Basit, "Enhanced gain and broadband of endfire antenna by using I-shaped resonator structures," *International Journal of RF and Microwave Computer-Aided Engineering*, vol. 28, 09/01 2018, doi: 10.1002/mmce.21519.
- [73] M. Labidi, R. Salhi, and F. Choubani, "A design of metamaterial multi-band bowtie antenna based on omega-shaped resonator," *Applied Physics A*, vol. 123, 04/06 2017, doi: 10.1007/s00339-017-0924-3.
- [74] Paras, D. Pandey, and S. Kumar, "Multiband Metamaterial Antenna with Omega Shaped SRR Structure for Wireless Communication," 11/05 2018.
- [75] Y.-X. Zhang, S. Qiao, W. Huang, W. Ling, L. Li, and S.-g. Liu, *Asymmetric single-particle triple-resonant metamaterial in terahertz band*. 2011, pp. 073111-073111.
- [76] S. Rout, "Active Metamaterials for Terahertz Communication and Imaging," 2016.
- [77] E. A. Hajlaoui and H. Trabelsi, "Improvement of Circularly Polarized Slot-Patch Antenna Parameters by Using Electromagnetic Band Gap Structures," *Journal of Microwaves, Optoelectronics and Electromagnetic Applications*, vol. 15, no. 4, pp. 428-440, 2016.
- [78] M. Fouad, A.-H. Shaalan, and K. Awadalla, *Design and simulation of a single fed multi-band circularly polarized microstrip antenna with slots*. 2015, pp. 71-79.
- [79] E. Yablonovitch, "Inhibited Spontaneous Emission in Solid-State Physics and Electronics," *Physical Review Letters*, vol. 58, no. 20, pp. 2059-2062, 05/18/1987, doi: 10.1103/PhysRevLett.58.2059.
- [80] V. Radisic, Y. Qian, R. Coccioli, and T. Itoh, *Novel 2-D Photonic Bandgap Structure for Microstrip Lines*. 1998, pp. 69-71.
- [81] M. Islam and M. S. Alam, *Design of High Impedance Electromagnetic Surfaces for Mutual Coupling Reduction in Patch Antenna Array*. 2013, pp. 143-155.

- [82] G. Niyomjan and Y. Huang, *An Accurate and Simple Design of High Impedance Surface Structure Using an Enhanced Effective Medium Method*. 2007, pp. 372-375.
- [83] F. Yang and Y. Rahmat-Samii, *Microstrip Antennas Integrated with Electromagnetic Band-Gap (EBG) Structures: A Low Mutual Coupling Design for Array Applications*. 2003, pp. 2936-2946.
- [84] M. R. Abkenar and P. Rezaei, "Design of a novel EBG structure and its application for improving performance of a low profile antenna," in *2011 19th Iranian Conference on Electrical Engineering*, 17-19 May 2011 2011, pp. 1-5.
- [85] A. Abdelraheem, M. Abdalla, M. Hessen, and A. Abdelsallam, *Surface Wave and Mutual Coupling Reduction Between Two Element Array MIMO Antenna*. 2013.
- [86] D. Sievenpiper, L. Zhang, R. F. Broas, N. G. Alexopolous, and E. Yablonovitch, "High-impedance electromagnetic surfaces with a forbidden frequency band," *IEEE Transactions on Microwave Theory and techniques*, vol. 47, no. 11, pp. 2059-2074, 1999.
- [87] Sievenpiper and D. Frederic, *High-impedance electromagnetic surfaces*. 2019.
- [88] C. Watts, X. Liu, and W. Padilla, *Metamaterial Electromagnetic Wave Absorbers*. 2012, pp. OP98-120, OP181.
- [89] A. Dubey and T. C. Shami, *Metamaterials in Electromagnetic Wave Absorbers*. 2012, pp. 261-268.
- [90] R. C Jain, *Understanding Electromagnetic Wave Absorbers*. 2015, pp. 35-43.
- [91] N. I. Landy, S. Sajuyigbe, J. J. Mock, D. R. Smith, and W. J. J. P. r. l. Padilla, "Perfect metamaterial absorber," vol. 100, no. 20, p. 207402, 2008.
- [92] K. Hatakeyama and T. Inui, "Electromagnetic wave absorber using ferrite absorbing material dispersed with short metal fibers," *IEEE Transactions on Magnetics*, vol. 20, no. 5, pp. 1261-1263, 1984, doi: 10.1109/TMAG.1984.1063424.
- [93] X. Liu, T. Starr, A. F. Starr, and W. J. Padilla, "Infrared Spatial and Frequency Selective Metamaterial with Near-Unity Absorbance," *Physical Review Letters*, vol. 104, no. 20, p. 207403, 05/19/ 2010, doi: 10.1103/PhysRevLett.104.207403.
- [94] B. Munk, "Frequency selective surfaces : theory and design," (in English), 2000. [Online]. Available: <http://public.eblib.com/choice/publicfullrecord.aspx?p=226559>.
- [95] X. Fang, C. Y. Zhao, and H. J. F. i. E. Bao, "Design and analysis of Salisbury screens and Jaumann absorbers for solar radiation absorption," journal article vol. 12, no. 1, pp. 158-168, March 01 2018, doi: 10.1007/s11708-018-0542-6.
- [96] A. Motevasselian and B. L. G. Jonsson, *Partially Transparent Jaumann-Like Absorber Applied to a Curved Structure*. 2011.
- [97] D. Schurig, J. J. Mock, and D. R. Smith, *Electric-Field-Coupled Resonators for Negative Permittivity Metamaterials*. 2006, pp. 041109-041109.
- [98] J. Batchelor, B. Sanz-Izquierdo, E. A. Parker, and J.-B. Robertson, "Tuneable frequency selective surface," 2014.
- [99] D. Song Wang, S.-W. Qu, and C. Hou Chan, "Frequency Selective Surfaces," 2016.
- [100] N. I. Landy, C. M. Bingham, T. Tyler, N. Jokerst, D. R. Smith, and W. J. Padilla, "Design, theory, and measurement of a polarization-insensitive absorber for terahertz imaging," *Physical Review B*, vol. 79, no. 12, p. 125104, 03/05/ 2009, doi: 10.1103/PhysRevB.79.125104.

- [101] D. Smith, D. Vier, T. Koschny, and C. J. P. r. E. Soukoulis, "Electromagnetic parameter retrieval from inhomogeneous metamaterials," vol. 71, no. 3, p. 036617, 2005.
- [102] F. Bagci and B. Akaoglu, *Consequences of Unit Cell Design in Metamaterial Perfect Absorbers*. 2016, pp. 792-796.
- [103] O. Ayop, M. K. A. Rahim, N. A. Murad, and H. A. J. A. P. A. Majid, "Metamaterial absorber based on circular ring structure with and without copper lines," vol. 117, no. 2, pp. 651-656, 2014.
- [104] B. Ma, S. Liu, X.-K. Kong, Y. Jiang, J. Xu, and H. Yang, "A Novel Wide-band Tunable Metamaterial Absorber Based On Varactor Diode/Graphene," *Optik - International Journal for Light and Electron Optics*, vol. 127, 12/01 2015, doi: 10.1016/j.ijleo.2015.11.168.
- [105] J. Wang *et al.*, "Three dimensional microwave metamaterials absorbers composed of coplanar electric and magnetic resonators," *Progress in Electromagnetics Research Letters*, vol. 7, pp. 15-24, 01/01 2009, doi: 10.2528/PIERL09012003.
- [106] J. Song, L. Wang, M. Li, and J. Dong, "A dual-band metamaterial absorber with adjacent absorption peaks," *Journal of Physics D: Applied Physics*, vol. 51, no. 38, p. 385105, 2018/08/21 2018, doi: 10.1088/1361-6463/aad7e1.
- [107] A. Hoque, M. Tariqul Islam, A. F. Almutairi, T. Alam, M. Jit Singh, and N. Amin, "A Polarization Independent Quasi-TEM Metamaterial Absorber for X and Ku Band Sensing Applications," vol. 18, no. 12, p. 4209, 2018. [Online]. Available: <http://www.mdpi.com/1424-8220/18/12/4209>.
- [108] O. Ayop, M. K. A. Rahim, N. Murad, N. A. Samsuri, and R. Dewan, "Triple Band Circular Ring-Shaped Metamaterial Absorber for X-Band Applications," *Progress In Electromagnetics Research M*, vol. 39, pp. 65-75, 10/06 2014, doi: 10.2528/PIERM14052402.
- [109] H. Li, L. Hua Yuan, B. Zhou, X. Peng Shen, Q. Cheng, and T. Jun Cui, "Ultrathin multiband gigahertz metamaterial absorbers," *Journal of Applied Physics*, vol. 110, pp. 014909-014909, 07/12 2011, doi: 10.1063/1.3608246.
- [110] W. Zuo, Y. Yang, X. He, C. Mao, T. J. I. A. Liu, and W. P. Letters, "An Ultrawideband Miniaturized Metamaterial Absorber in the Ultrahigh-Frequency Range," vol. 16, pp. 928-931, 2017.
- [111] D. Sood and C. C. Tripathi, *A compact ultrathin ultra-wideband metamaterial microwave absorber*. 2017, pp. 514-528.
- [112] T. T. Nguyen and S. Lim, "Design of Metamaterial Absorber using Eight-Resistive-Arm Cell for Simultaneous Broadband and Wide-Incidence-Angle Absorption," *Scientific Reports*, vol. 8, 12/01 2018, doi: 10.1038/s41598-018-25074-8.
- [113] M. Yoo and S. Lim, "Switchable Electromagnetic Reflector/Absorber with Electric-Field-Coupled LC Resonator," *Electromagnetics*, vol. 34, no. 5, pp. 421-429, 2014/07/04 2014, doi: 10.1080/02726343.2014.910375.
- [114] B. Slovick, Z. G. Yu, M. Berding, and S. J. P. R. B. Krishnamurthy, "Perfect dielectric-metamaterial reflector," vol. 88, no. 16, p. 165116, 2013.
- [115] L. Akhoondzadeh-Asl, J. Nourinia, C. Ghobadi, and P. Hall, "Influence of element shape on the bandwidth of artificial magnetic conductors," *Journal of Electromagnetic Waves and Applications*, vol. 21, no. 7, pp. 929-946, 2007.
- [116] M. M. Hasan, M. R. I. Faruque, S. S. Islam, and M. T. Islam, "A New Compact Double-Negative Miniaturized Metamaterial for Wideband Operation," (in eng), *Materials (Basel)*, vol. 9, no. 10, p. 830, 2016, doi: 10.3390/ma9100830.

- [117] R. M. Walser, A. P. Valanju, W. Win, M. Becker, R. W. Bene, and A. B. Buckman, *New smart materials for adaptive microwave signature control*. 1993.
- [118] I. Lindell and A. Sihvola, *Electromagnetic Boundaries with PEC/PMC Equivalence*. 2016.
- [119] R. Dewan *et al.*, *Artificial magnetic conductor for various antenna applications: An overview*. 2017.
- [120] R. Sadaf Anwar and H. Ning, *Frequency Selective Surfaces: A Review*. 2018, p. 1689.
- [121] A. Kaur and G. Saini, *Review of Various Designs of Periodic Structures for Frequency Selective Surfaces*. 2016, pp. 246-250.
- [122] N. K. Chahat Jain, G. J. I. J. o. E. T. Kaur, and A. Engineering, "Artificial magnetic conductor for miniaturized antenna applications-A Review," 2012.
- [123] K. k. Varikuntla and R. Singarav, *Review on Design of Frequency Selective Surfaces based on Substrate Integrated Waveguide Technology*. 2018, pp. 101-110.
- [124] M. Abu and M. K. A. Rahim, *Single-band and Dual-band Artificial Magnetic Conductor Ground Planes for Multi-band Dipole Antenna*. 2012, pp. 999-1006.
- [125] E. Hussin, *Designing Artificial Magnetic Conductor at 2.45 GHz for Metallic Detection in RFID Tag Application*. 2014, pp. 427-435.
- [126] F. Yang and Y. Rahmat-Samii, *Reflection Phase Characterizations of the EBG Ground Plane for Low Profile Wire Antenna Applications*. 2003, pp. 2691-2703.
- [127] B. Zhu, Y. Feng, J. Zhao, C. Huang, and T. Jiang, *Switchable Metamaterial Reflector/Absorber for Different Polarized Electromagnetic Waves*. 2010.
- [128] S. P. Rea, D. Linton, E. Orr, and J. McConnell, *Broadband high-impedance surface design for aircraft HIRF protection*. 2006, pp. 307-313.
- [129] W. Ramos, R. Mesquita, and E. Silva, *Design of the artificial magnetic conductors with meander line elements: Reduction in the first and second resonant frequencies*. 2017, p. 075801.
- [130] J. Li, H. Huo, J. Chen, S. Zhu, H. Shi, and A. Zhang, "Miniaturised artificial magnetic conductor and its application in unidirectional circularly polarised slot antenna design," *IET Microwaves, Antennas & Propagation*, vol. 12, no. 12, pp. 1885-1889, 2018, doi: 10.1049/iet-map.2018.0108.
- [131] H. Liu, K. L. Ford, and R. J. Langley, "Miniaturised artificial magnetic conductor design using lumped reactive components," *Electronics Letters*, vol. 45, no. 6, pp. 294-295, 2009, doi: 10.1049/el.2009.3369.
- [132] C. Ma *et al.*, "Antenna reflector based on air loaded AMC structure," in *2017 International Applied Computational Electromagnetics Society Symposium (ACES)*, 1-4 Aug. 2017 2017, pp. 1-2.
- [133] N. Ojaroudi Parchin, H. Jahanbakhsh, Y. Al-Yasir, R. Abd-Alhameed, A. Abdulkhaleq, and J. Noras, *Recent Developments of Reconfigurable Antennas for Current and Future Wireless Communication Systems*. 2019, p. 128.
- [134] T. Song, Y. Lee, D. Ga, and J. Choi, *A Polarization Reconfigurable Microstrip Patch Antenna using PIN Diodes*. 2012, pp. 616-618.
- [135] D. Niture, S. S. Gurame, and S. P. Mahajan, *A Pattern and Polarization Reconfigurable Antenna For WLAN Application*. 2018, pp. 303-308.
- [136] F. Dicandia, S. Genovesi, and A. Monorchio, *Characteristic modes analysis for pattern reconfigurable antenna design*. 2016, pp. 417-418.

- [137] J. P. Turpin, J. A. Bossard, K. L. Morgan, D. H. Werner, and P. L. Werner, *Reconfigurable and Tunable Metamaterials: A Review of the Theory and Applications*. 2014, pp. 1-18.
- [138] B. Zhu, Y. Feng, J. Zhao, C. Huang, and T. J. A. P. L. Jiang, "Switchable metamaterial reflector/absorber for different polarized electromagnetic waves," vol. 97, no. 5, p. 051906, 2010.
- [139] D. Lee, H. Jeong, and S. J. S. R. Lim, "Electronically switchable broadband metamaterial absorber," vol. 7, no. 1, p. 4891, 2017.
- [140] M. D. Gregory *et al.*, "A Low Cost and Highly Efficient Metamaterial Reflector Antenna," *IEEE Transactions on Antennas and Propagation*, vol. 66, no. 3, pp. 1545-1548, 2018, doi: 10.1109/TAP.2017.2781151.
- [141] H. Wakatsuchi, S. Greedy, C. Christopoulos, and J. Paul, *Customised broadband metamaterial absorbers for arbitrary polarisation*. 2010, pp. 22187-98.
- [142] A. Chandra Kundu and I. Awai, *Control of attenuation pole frequency of a dual-mode microstrip ring resonator bandpass filter*. 2001, pp. 1113-1117.
- [143] H. Y Chen, X. Y Hou, and L. J Deng, *A Novel Microwave Absorbing Structure Using FSS Metamaterial*. 2019.
- [144] M. Agarwal and M. K. Meshram, "Metamaterial-based dual-band microwave absorber with polarization insensitive and wide-angle performance," *AIP Advances*, vol. 8, no. 9, p. 095016, 2018, doi: 10.1063/1.5020702.
- [145] J. Shaw, *Radiometry and the Friis transmission equation*. 2013, pp. 33-37.
- [146] P. Eskelinen, "Modern millimeter-wave technologies [Book Review]," *IEEE Aerospace and Electronic Systems Magazine*, vol. 17, no. 7, pp. 38-39, 2002, doi: 10.1109/MAES.2002.1017794.
- [147] T. Li, H. Zhai, C. Liang, and Q. Li, "Study of coupling properties of the square split ring resonator," *Xi'an Dianzi Keji Daxue Xuebao/Journal of Xidian University*, vol. 40, pp. 26-29+35, 02/01 2013, doi: 10.3969/j.issn.1001-2400.2013.01.005.
- [148] C. Saha, J. Siddiqui, D. Guha, and Y. M. M. Antar, *Square Split Ring Resonators: Modelling of resonant frequency and polarizability*. 2008, pp. 1-3.
- [149] Q. Wu, F. Lan, Y. Zhang, H. Zeng, Z. Yang, and X. Gao, "Polarization insensitivity in square split-ring resonators with asymmetrical arm widths," *Chinese Optics Letters*, vol. 13, pp. 101601-101605, 10/10 2015, doi: 10.3788/COL201513.101601.
- [150] X. Shen, T. Jun Cui, J. Zhao, H. Feng Ma, W. X. Jiang, and H. Li, *Polarization-independent wide-angle triple-band metamaterial absorber*. 2011, pp. 9401-7.
- [151] K. B. Alici, F. Bilotti, L. Vegni, and E. J. J. o. A. P. Ozbay, "Experimental verification of metamaterial based subwavelength microwave absorbers," vol. 108, no. 8, p. 083113, 2010.
- [152] H. Luo, Y. Cheng, and R. Z. Gong, "Numerical study of metamaterial absorber and extending absorbance bandwidth base on multi square patches," *The European Physical Journal B - Condensed Matter and Complex Systems*, vol. 81, pp. 387-392, 06/01 2011, doi: 10.1140/epjb/e2011-20115-1.
- [153] H. Torun, S. Sadeghzadeh, H. Bilgin, and A. Yalcinkaya, "A Suspended Array of Square Patch Metamaterial Absorbers for Terahertz Applications," *Procedia Engineering*, vol. 120, pp. 20-25, 12/31 2015, doi: 10.1016/j.proeng.2015.08.557.

- [154] M. Hosseinipanah and Q. Wu, *Equivalent Circuit Model for Designing of Jerusalem Cross-Based Artificial Magnetic Conductors*. 2009.
- [155] M. Hosseini and M. Hakkak, *Characteristics Estimation for Jerusalem Cross-Based Artificial Magnetic Conductors*. 2008, pp. 58-61.
- [156] Q. Luo, H. Tian, Z. Huang, X. Wang, Z. Guo, and Y. Ji, "Unidirectional Dual-Band CPW-Fed Antenna Loaded with an AMC Reflector," *International Journal of Antennas and Propagation*, vol. 2013, pp. 1-10, 11/18 2013, doi: 10.1155/2013/875281.

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.*
 - Single / 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.