WIDEBAND MOSAIC FREQUENCY SELECTIVE SURFACE FOR DICHROIC SURFACE, ABSORBER AND DIRECTIVE ANTENNA APPLICATIONS

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DEDICATION

To myself, thank you for being highly courageous, hardworking, and never giving up.

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ABSTRACT

Acquiring a highly optical transparent feature on the wideband frequency selective surface (FSS) is challenging. Generally, the wideband response can be achieved using the multilayer FSS configurations, leading to high fabrication cost and thick end product. The innovation of the FSS structural element allowed the wideband frequency response to be achieved by using the single-layer configuration, but unsuitable for optical transparency application due to the wide trace width of the structural element. The main objective of the thesis is to assess the performance of mosaic frequency selective surface (MFSS), which comprises a combination of the Koch fractal on the inner and outer loops of the basic double hexagonal loops structural element. The narrow trace width of the MFSS allowed the structural element to be further utilised for optical transparency application. The performance comparison between the opaque MFSS (with FR4 substrate) and the transparent MFSS (with polycarbonate substrate) was studied and investigated thoroughly. The opaque MFSS and transparent MFSS (~ 70.3 % of transparency level) yielded wideband bandstop and bandpass frequency responses with a low cross-polarisation, T_{yx} (-37 dB), yet the angular stability was limited to only 25°. The MFSS performance under the influence of the array and substrate configurations (MFSS, MFSS2 and MFSS3) were also investigated in detail. With increased array and substrate configurations, broader bandwidth (BW) was achieved for the first and second bandstop frequency responses, while vice versa for the bandpass frequency response. The optical transparency of the MFSSs remains constant with a low T_{yx} (< -35 dB). Within the lower frequency region, the MFSS2 and MFSS3 had a high angular- and polarisation stability of up to 30° and 40°, respectively. However, the scan blindness phenomenon became more obvious within higher frequency regions. The MFSS structural element was further proposed for dichroic surface, absorber, and directive antenna applications. The complementary MFSS (CMFSS) structural element was applied for the dichroic surface application. The design requirement was to permit the reflection and the transmission of the EM wave at 183 GHz and 325 GHz, respectively, and the T_{yx} levels were < -68 dB. The CMFSS was also highly insensitive towards angular- and polarisation variations of up to 45°. For the absorber application, the metallic MFSS periodic array was replaced by the resistive MFSS (RMFSS) periodic array, which was fabricated on the thin Polyethylene Terephthalate (PET) substrate backed with a metal plate to establish a very thin wideband absorber. Even though the wideband absorption with fractional bandwidth of 132 % is achieved by using the multilayer MFSS absorber, yet the relative thickness was only $\lambda_L/15$. The MFSS absorber was also insensitive to angular- and polarisation variation of up to 35°. Lastly, the monopole antenna was associated with the studied MFSS absorber to have a low-profile directive antenna. With the MFSS absorber, the maximal directivity with high front-to-back ratio was obtained by placing the absorber at only a short distance from the antenna ($d = 2\lambda_{f_r}/25$). This absorber can be used to avoid or control the perturbation near the monopole antenna. The simulation process (Computer Simulation Technology Microwave Studio (CST MWS)), the fabrication process (laser etch and screen-printing techniques), and the measurement process (free space and radiation pattern measurements) varied depending on the applications. The simulated results were in good agreement with the measured results, which validated the utilisation of MFSS for various applications.

ABSTRAK

Untuk memperoleh ciri lutsinar optik yang tinggi pada permukaan frekuensi terpilih (FSS) jalur lebar adalah sesuatu yang mencabar. Secara amnya, sambutan jalur lebar boleh dicapai menggunakan konfigurasi FSS berbilang lapisan, yang membawa kepada kos fabrikasi yang tinggi dan keluaran produk yang tebal. Inovasi yang dilakukan pada unsur struktur FSS membolehkan sambutan frekuensi jalur lebar dicapai dengan menggunakan konfigurasi selapis, tetapi tidak sesuai untuk penggunaan lutsinar optik kerana jejak lebar unsur struktur yang lebar. Objektif utama tesis ini adalah untuk menilai prestasi mozek permukaan frekuensi terpilih (MFSS), yang terdiri daripada gabungan fraktal Koch pada gelung dalam dan luar bagi unsur struktur asas gelung heksagon berganda. Jejak lebar MFSS yang halus membolehkan unsur struktur digunakan selanjutnya untuk penggunaan lutsinar optik. Perbandingan prestasi antara MFSS legap (dengan substrat FR4) dan MFSS lutsinar (dengan substrat Polycarbonate) kemudiannya dikaji dan disiasat dengan teliti. MFSS legap dan MFSS lutsinar (~ 70.3 % aras lutsinar) menghasilkan sambutan frekuensi jalur lebar untuk batas jalur dan lulus jalur dengan pengutuban silang, T_{yx} (-37 dB) yang rendah, namun kestabilan sudut terhad kepada 25° sahaja. Prestasi MFSS di bawah pengaruh konfigurasi tatasusunan dan substrat (MFSS, MFSS2 dan MFSS3), turut disiasat secara terperinci. Dengan penambahan konfigurasi tatasusunan dan substrat, lebar jalur (BW) yang lebih luas telah dicapai untuk sambutan frekuensi batas jalur pertama dan kedua, manakala sebaliknya untuk sambutan frekuensi lulus jalur. Lutsinar optik semua MFSS kekal pemalar dengan ciri T_{yx} yang sangat rendah (tahap T_{yx} < -35 dB). Untuk kawasan frekuensi yang rendah, MFSS2 dan MFSS3 mempunyai kestabilan yang tinggi terhadap sudut dan pengutuban masing-masing sehingga 30° dan 40°. Walau bagaimanapun, dalam kawasan frekuensi yang lebih tinggi, kejadian fenomena imbas buta menjadi lebih jelas. Unsur struktur MFSS selanjutnya dicadangkan untuk aplikasi permukaan dikroik, penyerap, dan antena arahan. Unsur struktur MFSS pelengkap (CMFSS) telah digunakan untuk aplikasi permukaan dikroik. Keperluan rekabentuk adalah untuk membenarkan pantulan dan penghantaran gelombang EM masing-masing pada 183 GHz dan 325 GHz, dan tahap T_{yx} adalah < -68 dB. CMFSS juga sangat tidak sensitif terhadap variasi sudut dan pengutuban sehingga 45°. Untuk aplikasi penyerap, tatasusunan berkala MFSS logam digantikan dengan tatasusunan berkala MFSS berintangan (RMFSS), yang difabrikasi pada substrat nipis *Polyethylene Terephthalate* (PET) yang disandarkan dengan plat logam untuk membentuk penyerap jalur lebar yang sangat nipis. Walaupun penyerapan jalur lebar dengan lebar-jalur pecahan sebanyak 132 % dicapai dengan menggunakan penyerap MFSS berbilang lapisan, namun ketebalan nisbi hanya $\lambda_L/15$. Penyerap MFSS juga tidak sensitif terhadap variasi sudut dan pengutuban sehingga 35°. Akhir sekali, ekakutub antena disekutukan dengan penyerap MFSS yang dikaji untuk digunakan sebagai antena arahan profil rendah. Dengan penyerap MFSS, arahan maksimum dengan nisbah depan ke belakang yang tinggi diperoleh dengan meletakkan penyerap hanya pada jarak yang dekat dari antena ($d = 2\lambda_{f_r}/25$). Penyerap tersebut dapat digunakan untuk mengelak atau mengawal gangguan berdekatan dengan ekakutub antena. Proses penyelakuan (*Computer Simulation Technology Microwave Studio* (CST MWS)), proses fabrikasi (teknik punar laser dan cetak layar), dan proses pengukuran (pengukuran ruang bebas dan corak sinaran), adalah berbeza-beza bergantung pada aplikasi. Keputusan penyelakuan adalah hampir sama dengan keputusan pengukuran, yang mengesahkan penggunaan MFSS untuk pelbagai aplikasi.

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LIST OF ABBREVIATIONS

FSS	-	Frequency Selective Surface
EM	-	Electromagnetic
THz	-	Terahertz
FBW	-	Fractional Bandwidth
FBR	-	Front-To-Back Ratio
ADHD	-	Attention Deficit Hyperactivity Disorder
DNA	-	Deoxyribonucleic Acid
AMC	-	Artificial Magnetic Conductor
EBG	-	Electromagnetic Bandgap
CST MWS	-	Computer Simulation Technology
MFSS	-	Mosaic Frequency Selective Surface
CMFSS	-	Complementary Mosaic Frequency Selective Surface
PET	-	Polyethylene Terephthalate
BW	-	Bandwidth
ECM	-	Equivalent Circuit Model
TM	-	Transverse Magnetic
TE	-	Transverse Electric
IFS	-	Iterated Function System
AFA	-	Antenna-Filter-Antenna
DSSLFSS	-	Double-Sided Single-Layer FSS
ITO	-	Indium Tin Oxide
AgHT	-	Silver-Coated Polyester Film
FTO	-	Fluorine-Doped Tin Oxide
EHF	-	Extremely High Frequency
Sub-MMW	-	Submillimetre Wave
GPS	-	Global Positioning System
FIT	-	Finite Integration Technique
DHLFSS	-	Basic Double Hexagonal Loops FSS
IDHLFSS	-	Interconnected Double Hexagonal Loops FSS

MFSS-KF1	-	First Iteration Level of Koch Fractal Of The MFSS
MFSS-KF2	-	Second Iteration Level of Koch Fractal Of The MFSS (MFSS-KF2)
RO	-	Rotation Orientation
MFSS2	-	Double-Sided MFSS
MFSS3	-	Multilayered MFSS
d	-	Air Spacer Thickness
SR	-	Sheet Resistance Of The Resistive MFSS Layer
PLD	-	Power loss density
MA	-	Monopole Antenna
PECMA	-	Perfect Electric Conductor Loaded Monopole Antenna
MFSSAMA	-	MFSS Absorber Loaded Monopole Antenna
PEC	-	Perfect Electric Conductor
d	-	Separation Distance
SMA	-	Sub-Miniature Version A
FG	-	Forward Gain
BG	-	Backward Gain

LIST OF SYMBOLS

f_r	-	Resonant Frequency
S_{21}	-	Transmission Coefficient
E_i	-	Incident Plane Wave
E_t	-	Transmitted Wave
E_r	-	Reflected Wave
Γ	-	Reflection Coefficient
T	-	Transmission Coefficient
L	-	Inductance
C	-	Capacitance
β	-	Propagation Constant
β_{sw}	-	Surface Wave Propagation Constant
λ	-	Free-Space Wavelength
ε_r	-	Permittivity
θ_{air}	-	Angle of Incidence in the Free Space
θ_s	-	Angle of Incidence Inside the Dielectric Substrate
$\theta_i = 0°$	-	Normal Incident
η	-	Intrinsic Impedance (Complex)
γ	-	Propagation Constant
$\theta_i \neq 0°$	-	Oblique Angles of Incidence
$E_\perp$	-	Electric Field Is Perpendicular to the Plane of Incidence
$E_\parallel$	-	Electric Field Is Parallel to the Plane of Incidence
k_1	-	Propagation Constant of Region 1
k_2	-	Propagation Constant of Region 2
θ_i	-	Angle of Incident
θ_r	-	Angle of Reflection
θ_t	-	Angle of Transmission
η_1	-	Intrinsic Impedance of Region 1
η_2	-	Intrinsic Impedance of Region 2
θ_b	-	Brewster Angle

λ	-	Wavelength
L_E	-	Electrical Length
ε_{eff}	-	Effective Permittivity
c	-	Speed of Light
w	-	Two-Dimensional Affine Transformation
W	-	*Hutchinson Operator*
A_∞	-	The Attractor of The IFS
D	-	Self-Similar Dimension
sf	-	Scaling Fraction
N	-	Copies of the Original Geometry
k	-	Iteration Level
Z_R	-	Absorber Surface Impedance
Z_{FSS}	-	Impedance of the FSS
Z_d	-	Surface Impedance of the Grounded Dielectric Substrate
Z_m^{TE}	-	Characteristic Impedance of the Slab for TE
Z_m^{TM}	-	Characteristic Impedance of the Slab for TM
$Re(Z_R)$	-	Real of the Input Impedance
$Im(Z_R)$	-	Imaginary of the Input Impedance
Z_o	-	Free Space Impedance
R_{opt}	-	Optimized Equivalent Resistive Impedance
S_{11}	-	Reflection Coefficient
R_{xx}	-	Co-Polarized Reflection Coefficient
T_{xx}	-	Co-Polarized Transmission Coefficient
T_{yx}	-	Cross-Polarized Transmission Coefficient
R_s		Sheet Resistance
ρ		Electrical Resistivity
t		Thickness Of The Resistive Ink.
L_{MA}	-	Length of the Monopole Antenna
$tan\delta$		Loss Tangent
σ		Conductivity
f_L	-	Lower Cut-Off Frequencies
f_H	-	Higher Cut-Off Frequencies

f_c	-	Center Frequency
R1	-	Length Of Outer Loop
R2	-	Length Of Inner Loop
W1	-	Width Of The Outer Loop
W2	-	Width Of Inner Loop
L	-	Side Length Of The Substrate
a	-	Periodicity Of Unit Cell
P	-	Width Of The Substrate
H	-	Height Of The Triangular Lattice Arrangement
T	-	Optical Transparency
TA	-	Total Area Of The Unit Cell
MA	-	Metal Element Area Of The Unit Cell

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CHAPTER 1

INTRODUCTION

1.1 Research Background

The frequency selective surfaces (FSS) have shown good promise as a spatial filter for telecommunication applications. Its attractive design has urged many researchers to explore and innovate the FSS geometry over the past few years. The American physicist, David Rittenhouse, pioneered the study on the FSS in 1786 after he discovered that some of the colours of the light spectrum were filtered out through a silk scarf while observing a lamp (1). According to Munk (2), FSS is a periodic array composed of conducting patch or aperture structural elements. The filtering characteristics of a FSS, such as low pass, high pass, bandpass, and band-stop frequency responses, can be established depending on the structural elements.

On that note, the patch structural element of the FSS allows the transmission of the high frequency while blocking and reflecting the low frequency, where it acts as a high pass filter. Meanwhile, the slot (complementary patch) structural element can provide low pass filtering characteristics, according to the Babinet principle. The combination of different structural elements allows the customisation of the FSS frequency responses (bandpass and bandstop) to meet the design specification requirement for different applications (3). When the FSS was exposed to the incident electromagnetic (EM) wave, the scattered wave generated a specific frequency response based on the customised structural elements. The filtering characteristics of these frequency responses are strongly influenced by the structural element, the unit cell dimension, the dielectric loading effects, multilayer, cascade configuration, etc., of the FSS.

Due to its capability in redirecting and controlling the EM wave, FSS has been suggested to be applied for various applications within different EM spectrums such as dichroic surface, absorber, high gain directive antenna, and for the FSS to be optically transparent to provide additional security, especially in the development of the smart cities.

Future interest in the rapid evolution of 5G technology and smart cities requires antennas to be integrated into existing urban infrastructure, to provide high-speed interconnectivity between the end-users and the signal provider (4). However, in pursuit of integrating new technology and high-speed connectivity, introducing the antennas into a pre-existing system could jeopardise secure communications and the security of the infrastructure, especially within buildings such as hospitals, government agencies, industrial factories, etc. Thus, the FSS is required to be also integrated to the existing infrastructures to provide separation or containment to a selected frequency. Plus, FSS could also act as transparent microwave filters to foster additional security across specified areas within the building.

On the other hand, rapid climate change is currently the main topic discussed worldwide. The spaceborne terahertz (THz) instrument technology, also known as the microwave sounder radiometer, is the current equipment that has been used to monitor and study the linked factors such as the temperature profiles, water vapour profiles that contributed to the mentioned issue, in which useful to forecast the weather and air quality (5). The radiometer typically utilised only a single mechanically scanned reflector antenna to collect the wide frequency range of radiation. This is because there are constraints such as the volume, cost, mass and energy consumption, in order to satisfy the satellite payload. The utilisation of FSS had been highly suggested to be used in the quasi-optical feed train to demultiplex the collected wide frequency range signal, allowing the specified linearly polarised signal to be obtained at the receiver (5).

Meanwhile, EM interference could cause the malfunction of a device or an instrument. As a solution, an absorber is suggested to reduce the arising issue. The metallic FSS based absorber and the resistive FSS based absorber had been suggested previously, where both absorbers offer different absorption characteristics and overall absorber compactness, which can provide absorptivity within different absorption spectrums (6).

For the directive antenna application, the main objective is to enhance the gain and reduce the back radiation of the antenna. Commonly, a quarter wavelength separation distance between the reflector and the antenna is required to meet the objective, which would not be suitable to establish the low-profile high gain directive antenna (7). Besides FSS and metamaterial-based absorbers, the resistive FSS based absorber has been suggested to reduce the separation distance, thus establishing a low-profile directive antenna. These mentioned applications are going to be thoroughly discussed in the following chapter.

1.2 Problem Statement

FSS has shown good promise as a spatial filter, which incorporates specific filtering characteristics with the attractive design of the FSS structure element (unit cell), bringing many advantages for future innovation and application. Generally, multilayer FSS configurations offer wideband filtering characteristics with improved FSS performance compared to single-layer FSS (8–11). However, the implementation cost, along with the size and thickness of the end product, are the main issues that cause disadvantages to the multilayer FSS configuration. Recently, the innovation of the FSS structural elements allows the wideband frequency response to be achieved using the single-layer FSS (12–16). However, due to the wide trace width of the structural element, the previous FSSs are unable to be further utilised for optical transparency applications. Therefore, it is a challenge to have a narrow trace width FSS structural element that can provide a wideband response (FBW > 50%), where the structural element can be further utilised for optical transparency application.

The FSS had been proposed to be optically transparent to decrease the visual impact of the FSS, where the transparency must be 50% and above, especially for the development of smart cities (4,17). Previously, a few techniques, such as the thin-film technique using transparent conductive materials (18), the meshed technique (19,20) and the screen-printing technique (21), have been explored to fabricate the FSS for optical transparency application. However, these reported techniques are unable to achieve the wideband frequency response objective. As mentioned previously, the wideband frequency response with improved FSS performance can be achieved by utilising the multilayer FSS configuration. However, up to now, the transparent multilayer FSS is rarely discussed and documented in previous work. For this work, the challenge is to have FSS with high optical transparency and wideband response, and to study the multilayer configuration effect on the FSS performance and transparency as multilayer transparent FSS is rarely documented.

On the other hand, for the dichroic surface application, the FSS had been proposed as an alternative to the drilled plate waveguide filter that had limitations, including high sensitivity towards oblique angles and high passband insertion loss, and lack of design flexibility (5). The FSS is positioned in the quasi-optical feed train of the radiometer, in which the FSS is used to demultiplex the collected wide-range signal, where the demultiplexed signal is then further directed to the individual channel mixer detectors. There is a necessity for the radiometer to address the THz frequencies, that critical for detecting other various gases, which allows the radiometer to gain additional meteorological information, which is highly essential for climate monitoring and weather forecasting (22,23). For dichroic surface application, the FSS must meet the important design specification – a very low passband insertion loss and very high bandstop isolation, with very low cross-polarisation level for the entire frequency range, especially within the bandpass frequency response (24). This work focuses on having a FSS that meets the design specification with a frequency separation ratio of 1:1.78 between the reflection frequency at 183 GHz and the transmission frequency of 325 GHz.

On the other hand, an absorber is normally used as a shielding instrument to prevent device malfunction commonly caused by EM interference. Traditionally, for resistive absorber applications, one of the pioneer innovations is the Salisbury screen. Conventionally, for the Salisbury screen, the resistive sheet must be placed at approximately a $\lambda/4$ from the backed ground plane for the absorber to achieve impedance matching to free space impedance within a narrow absorption spectrum

(25). A wider absorption spectrum can be achieved through a multilayer configuration (Jaumann absorber) (26). With a wide separation distance between the resistive sheet and the backed ground plane, it is impossible to have a very thin absorber that can provide a wideband absorption spectrum.

The metallic FSS based absorber with multilayer configuration is used to obtain a wideband absorption spectrum (6). However, the multilayer configuration led to a thick end product. After years of innovation, the metallic conducting layer of the FSS structural element is replaced with the resistive layer to establish the resistive FSS, where the backed ground plane can be placed at a separation distance that is lower than $\lambda/4$. The resistive FSS based absorber allowed a broader absorption spectrum to be achieved in a compact configuration. With single-layer absorber configuration, the basic structural elements, the multiple loops structural elements, and the integration between different resistive FSS structural elements allow wideband absorption spectrum (fractional bandwidth, FBW < ~100%) to be achieved with thin configuration (27–36). A broader absorption spectrum (FBW> ~100%) can be attained using the resistive FSS based absorber with multilayer configuration (37–39). However, the end product is thicker than the single-layer configuration. As summarised, the challenge here is to have a wideband absorption spectrum by utilising a very thin resistive FSS based absorber.

Finally, the direct exposure of the radiation from the antenna is harmful to the human body, especially when the antenna is placed directly or closed to the human body. Thus, numerous health problems (40) such as cancer risk, neurodegenerative diseases (Attention Deficit Hyperactivity Disorder (ADHD) like behaviour in children), and Deoxyribonucleic Acid (DNA) damage through the oxidative stress, keep arising these recent years that may be consequent to the long exposure to the EM radiation. To avoid or hide metallic perturbation from the antenna, and for an antenna to achieve impedance matching to the free space impedance and to be suitable for directive antenna application, an obstacle, in this case is a reflector must be placed at a wide separation distance or $\lambda/4$ from the antenna (7). Previously, the utilisation of reflectors or FSS redirects the radiation of the antenna to obtain maximal directivity with high front-to-back ratio (FBR). Even though the separation distance is lower than

$\lambda/4$, but the maximum FBR obtained is only higher than 10 (41–45). Recently, the utilisation of the absorbers, such as metamaterial absorbers, artificial magnetic conductor (AMC) and electromagnetic bandgap (EBG) absorbers, allowed higher FBR of more than 12 and up to 17.3 to be achieved. Unfortunately, a wide separation distance between the antenna and the absorber is required for the directive antenna to achieve impedance matching (7,46–48). The wide separation distance between the reflectors/absorbers and the antenna makes the antenna unfitting as a low-profile directive antenna. This work focuses on having a resistive FSS based absorber that is suitable to be utilised with the antenna to develop a low-profile directive antenna (higher FBR with very narrow separation distance).

1.3 Research Objectives

With the problem statements as stated in Section 1.2, the research objectives are as below:

(a) To propose and develop a new unit cell that provides wideband bandwidth (FBW > 50%) filtering mechanisms: bandpass and bandstop frequency responses, and also highly transparent.

(b) To characterise and analyse the influence of the array and substrate configurations on the performance improvement of the new transparent unit cell.

(c) To implement the similar unit cell for different FSS applications such as dichroic surface, absorber, and directive antenna.

1.4 Scope of Work

The research work focused on the study and development of a new unit cell design that could cater for wideband bandpass and bandstop frequency responses with very low cross-polarisation levels, and the performance of the unit cell is expected to be insensitive to angular- and polarisation variations. The new unit cell provides multi-freedom parameters in terms of geometry, printed support, single-layer or multilayer configurations, and unit cell's conductivity (metal conductor or resistive ink). For the first and second objectives, the proposed unit cell must meet the design specification such as narrow trace width with the ability to produce wideband frequency response. Due to the unique feature of the new unit cell, the unit cell also has the advantage of high optical transparency to reduce the visual impact of the FSS, which can be further employed for optical transparency applications. Moreover, the use of the screen-printing technique for the fabrication process gave a new perspective of having a transparent new unit cell in the most cost-effective way and easy integration of the unit cell on any existing surfaces. The wideband feature of the new unit cell performance can be further enhanced by utilising the multilayer array and substrate configurations, without affecting the new unit cell's optical transparency.

For the third objective, the same unit cell can be further used for various wideband applications – dichroic surface, absorber, and directive antenna applications. For the dichroic surface application, due to the industry collaboration with France company, the design specification that must be met such as low passband insertion loss, high bandstop isolation, low cross-polarisation level within the bandpass frequency response, with frequency separation ratio of 1:1.78 (183 GHz and 325 GHz).

For the absorber application, in this work, the main focus is to have a very thin absorber with a wideband absorption spectrum. Due to the very thin absorber configuration, it can be further explored for flexible applications. The performance of the unit cell can be further investigated when the flexible unit cell is applied on the conformal surface or the non-uniform surfaces, for future work. Finally, with the studied absorber, it is then applied together with the antenna. With the main objective to have maximal directivity with a higher FBR, the absorber is expected to be positioned in close proximity to the antenna, to realise the low-profile directive antenna.

The commercialised software Computer Simulation Technology Microwave Studio (CST MWS) is used as a simulation tool to study the new unit cell for various mentioned applications. The type of solver, the boundary conditions, and the required S-parameter were set accordingly to meet the simulation condition for various applications. The screen-printing technique is used to fabricate the new unit cell for optical transparency and absorber application. To validate the simulation result, the free space measurement technique is used to obtain the s-parameter result, especially for the optical transparency, dichroic surface and absorber applications. For the directive antenna, the results required to validate the simulated result are the s-parameter and the radiation pattern. The horn antennas and the vector network analyser are among the equipment employed for the measurement process.

1.5 Research Contributions

The main contribution of the research work is to develop and design a new unit cell that offers wideband bandpass and bandstop responses with very low cross-polarisation levels, through the integration between double hexagonal loops with Koch fractal structural elements. The new unit cell is named as mosaic frequency selective surface (MFSS), due to the unit cell geometry nature that is nearly similar to the mosaic pattern. Besides wideband filtering characteristics, the performance of the MFSS is also insensitive to angular- and polarisation variations, especially within the lower frequency region. However, for the higher frequency region, due to scan blindness and grating lobes phenomenon, the stability of the transparent MFSS performance was maintained up to only 25°.

In this research, due to the uniqueness of the MFSS, the unit cell can be further employed for optical transparency applications while maintaining wideband filtering characteristics. Based on previous work, it is currently still a challenge to have a transparent FSS with wideband frequency responses. Moreover, the unit cell can be directly fabricated onto the substrate using the cost-effective screen-printing technique (standard metal conductor ink) instead of utilising the costly transparent ink or complex mesh technique, to achieve high optical transparency feature. The MFSS unit cell is further applied for the dichroic surface, absorber and directive antenna applications.

For the dichroic surface application, the complementary MFSS unit cell positioned at 45° to the direction of propagation is used instead of the initial MFSS unit cell, to meet the design requirement that reflected the 183 GHz EM wave and allowed the 325 GHz EM wave to transmit, with very low cross-polarisation level for the entire frequency responses. The complementary MFSS (CMFSS) is also insensitive toward angular- and polarisation variation. For the absorber application, instead of using the metal conductor ink to fabricate the MFSS periodic array, the resistive ink MFSS periodic array with metal-backed is used to establish a wideband absorber with high angular- and polarisation stability. The MFSS absorber is expected to be compact with wideband absorptivity features. However, due to the limitation in maintaining the similar thickness of the resistive ink throughout the periodic array during the fabrication process, only an octave absorptivity of the MFSS absorber is achieved instead of two octave absorptivity in the MFSS absorber simulation. The same MFSS absorber is then associated with a monopole antenna, to be further utilised for the high gain directive antenna application. Within a very small separation between the MFSS absorber and the monopole antenna, high FBW was achieved, which indicated that the radiation pattern of the monopole antenna is redirected in order to have high forward gain with reduced backward radiation for directive antenna application. The realisation of the MFSS unit cell can be considered as an important step in having wideband responses that can be employed further in many other applications.

1.6 Thesis Outline

This thesis is structured into seven chapters. Chapter 1 presents the introductory background of the FSS and the current challenges faced (problem statements) with the aim of solving them (objectives). The contributions of the research toward new knowledge are also indicated in this chapter. Finally, the scope of the study and the outline of the thesis are included at the end of this chapter.

Chapter 2 explains the comprehensive literature review on the theoretical principle of the FSS operation and the pros and cons of the previous studies carried out by researchers worldwide. The performance of the FSS based on key factors such as the element type, lattice geometry and grating lobe phenomenon, Wood's Anomalies phenomenon, dielectric substrate, and angle of incidence of the EM wave and its polarisation, are reviewed critically in this chapter. Next, the fractal FSS structural element is also discussed in this chapter. The variation of the established fractal FSS structure to achieve single band FSS, multiband FSS and wideband FSS is also presented in this chapter. Following of this section, the usage of the FSS for various applications such as optical transparency, dichroic surface, absorber, and directive antenna applications are discussed thoroughly within this chapter.

Chapter 3 describes in detail the research methodology that covers the methods or approaches for the development of the MFSS, especially at the design, simulation, fabrication, and measurement stages. The CST MWS software is used to obtain the simulated transmission and reflection characteristics of the designated MFSS. The prototype of the opaque and transparent MFSS are fabricated by using the laser printing technique and screen-printing technique, respectively. Furthermore, the free space measurement process is conducted to validate the MFSS prototype simulated characteristics. The free space measurement has two different measurement setups focusing on two different microwave spectral bands: 2 GHz to 18 GHz and 18 GHz to 40 GHz. The simulation, fabrication, and measurement processes of the MFSS for various applications – optical transparency, dichroic surface, absorber, and directive antenna applications, have also been discussed thoroughly in this chapter.

Chapter 4 presents the step-by-step designing process of the MFSS, from the initial basic double hexagonal loop to the MFSS. The enhancement of BW is achieved through this designing process, especially at the bandstop and bandpass frequency responses. The effect of the Koch fractal iteration level on the MFSS on the reflection/transmission characteristics is also evaluated in this chapter. Moreover, in this chapter, the parametric analysis of the MFSS that contributed to the changes in the MFSS filtering performance is discussed thoroughly. Next, using the similar metallic pattern of the MFSS, the periodic array of the MFSS is fabricated on the transparent polycarbonate substrate to establish the optically transparent applications of the MFSS. The unit cell evolution of the opaque MFSS is presented to give a glimpse of the changes in the filtering performance of the opaque MFSS. It is proven that the transparent MFSS had the advantage of high optical transparency with wideband filtering features compared with the evolution of the opaque MFSS.

Chapter 5 discussed the effect of variation of array and substrate configurations on the filtering performance of the MFSS. The initial transparent MFSS has the metallic pattern periodic array on one side of the polycarbonate substrate. Next, the similar periodic array is fabricated on both sides of the polycarbonate substrate (MFSS2) and multilayer MFSS (MFSS3), and the changes in the performance filtering are observed. As the array and substrate configurations increase, the BW can be enhanced further, especially for bandstop frequency response, without affecting the optical transparency. While the BW of the bandpass frequency response is narrower and becomes selective at certain frequency range. On the other hand, the effect of parameters on the MFSS performance, such as the substrate thickness and permittivity, unit cell's misalignment, and unit cell's size dimension differential on the filtering characteristic of all of the MFSS, MFSS2 and MFSS3, are included in this chapter.

Chapter 6 outlines the applications of the MFSS for three different applications: dichroic surface, absorber, and directive antenna applications. For the dichroic surface application, due to the frequency range that had been specified, the complementary MFSS is applied to achieve the objective application as a replacement of the initial MFSS pattern. Instead of having the metallic pattern periodic array of the MFSS, with similar periodic array pattern, the resistive MFSS is fabricated on the thin Polyethylene Terephthalate (PET) substrate in order to have a compact wideband absorber. Finally, with the studied absorber, it is integrated to the monopole antenna, in order to have a high forward gain with reduced backward gain for the high gain directive antenna application. With the MFSS absorber, the forward gain of the monopole antenna can be enhanced by placing the absorber at only a short distance from the antenna, with the backward gain being reduced to a very low value.

Chapter 7 summarises the research contributions and the main findings of the research and outlines the future recommendations that draw from the current research.

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1. N. B. Mohamed Nafis, M. Himdi, M. K. A Rahim, O. Ayop, and R. Dewan, "Optically Transparent Tri-Wideband Mosaic Frequency Selective Surface with Low Cross-Polarisation," *Materials (Basel).*, vol. 15, no. 2, p. 622, Jan. 2022, doi: 10.3390/ma15020622.

2. N. B. Mohamed Nafis, M. K. A. Rahim, O. Ayop, H. A Majid, and S. Tuntrakool, "Characterization of the Koch Fractal Hexagonal Loop Frequency Selective Surface for X-band Application," *Indones. J. Electr. Eng. Comput. Sci.*, vol. 20, no. 2, p. 878, Nov. 2020, doi: 10.11591/ijeecs.v20.i2.pp878-886.

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1. N. B. M. Nafis, M. Himdi, M. K. A. Rahim, and F. Merzaki, "Mosaic Frequency Selective Surface with Wideband Response for the Optically Transparent and Absorber Applications," in *2022 16th European Conference on Antennas and Propagation (EuCAP)*, 2022, pp. 1–5, doi: 10.23919/EuCAP53622.2022.9769471.

2. N. B. Mohamed Nafis, M. K. A. Rahim, O. Ayop, F. Zubir, and H. A. Majid, "A Comparison of Various Double Loops Frequency Selective Surfaces in terms of Angular Stability," in *2019 International Symposium on Antennas and Propagation (ISAP)*, 2019, pp. 1–4.