CELL MINIATURIZATION FOR X-BAND FREQUENCY SELECTIVE SURFACE

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I dedicate my thesis work to my family and many friends. A special feeling of gratitude to my loving parents, Kok Kong and Choon Eng whose words of encouragement and push for tenacity ring in my ears. My brother Johnny, my sisters Jessie, and my niece, Jacqueline have never left my side and are very special.

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ABSTRACT

Electromagnetic Interference (EMI) generated by wireless devices can cause disturbance to electrical circuits. In this thesis, the Frequency Selective Surface (FSS) is proposed as the EMI shield for the interference control as it eliminates the need for power supply and blocking only the unwanted signals without interrupting the operation of other wireless devices. The contribution of this thesis comprise of the miniaturization technique employed for the dimension reduction of the unit cell FSS and the evaluation of the bending effect of the conformal FSS based on the semi-infinite modeling technique. All the designs and simulation works are completed utilizing the Computer Simulation Technology (CST) Microwave Studio software. First, the FSS is developed on the FR-4 substrate to perform as the band-stop planar FSS which support the attenuation over the X-band signals ranging from 8 GHz to 12 GHz. The evaluation of the planar FSS is performed using the unit cell boundary modelling. The miniaturization of the ring loop FSS is performed by adding four stubs at each $90°$ angle of the ring loop and four cross-dipole are embedded into convoluted ring loop FSS to further reduce the unit cell dimension. All the proposed unit cell geometries are modeled to accomplish the excellent transmission frequency response for normal and oblique incidence up to $60°$ cases at Transverse Electric (TE) and Transverse Magnetic (TM) polarizations. In order to ensure the FSS is competent to be employed as the EMI shield for the conformal structure, the proposed design is developed onto the flexible Polyethylene Terephthalate (PET) substrate. To prove the conformal suitability of the proposed planar design, the bending effects of the conformal FSS are investigated. The semi-infinite modeling allows modelling of the finite and infinite array in curved and uncurved directions, respectively. With the employment of this technique, the bending effects toward the performance of the proposed FSS at the normal angle of incidence for TE and TM polarizations are obtainable. From the results obtained, the convoluted ring loop FSS is the most sensitive to the bending effect while the ring loop FSS is the least sensitive to the bending effect. All the proposed FSS geometries are fabricated using either photolithography or inkjet printing technique. The manufactured prototypes are measured experimentally using bi-static measurement technique. All the proposed FSS provides minimum attenuation of - 25 dB at 10 GHz. The measurement results are shown to be similar with the simulation results. Hence, the proposed FSS can be employed in both planar and conformal structure.

ABSTRAK

Gangguan elektromagnet (EMI) yang terjana dari peranti-peranti wayarles boleh menyebabkan gangguan kepada litar elektrik. Dalam tesis ini Permukaan Frekeunsi Terpilih (FSS) dicadangkan sebagai perisai EMI bagi kawalan gangguan gelombang elektromagnet kerana ia menyingkir keperluan bekalan kuasa dan menghalang isyarat yang tidak dikehendaki tanpa menganggu operasi peranti-peranti wayarles yang lain. Sumbangan-sumbangan tesis ini merangkumi teknik pengecilan yang digunakan untuk mengurangkan dimensi sel unit FSS dan penilaian kesan lentur terhadap FSS menyebentuk berasakan teknik pemodelan separuh infinit. Kesemua reka bentuk dan kerja simulasi disiapkan dengan menggunakan perisian *Computer Simulation Technology (CST) Mircowave Studio*. Pertama, FSS yang dibangunkan atas substrat FR-4 untuk bertindak sebagai FSS menyatah jalur henti yang menyokong pelemahan isyarat dalam jalur-X yang berjulat dari 8 GHz hingga 12 GHz. Penilaian FSS menyatah dilakukan menggunakan pemodelan sempadan sel unit. Pengecilan FSS berbentuk gelung cincin dilakukan dengan menambah empat puntung pada setiap sudut $90°$ gelung cincin dan empat silang dwikutub dibenam pada gelung cincin berlingkar FSS untuk mengurangkan lagi dimensi sel unit. Kesemua geometri sel unit yang dicadangkan telah dimodel untuk mencapai sambutan frekeunsi penghantaran cemerlang untuk sudut tuju normal dan oblik sehingga kes-kes $60°$ bagi polarisasi *Transverse Electric* (TE) and *Transverse Magnetic* (TM). Untuk memastikan FSS berkemampuan digunakan sebagai perisai EMI pada struktur menyebentuk, reka bentuk yang dicadangkan dibangunkan pada substrat *Polyethylene Terephthalate* (PET) yang fleksibel. Untuk membuktikan kesesuaian menyebentuk reka bentuk menyatah yang dicadangkan, kesan lentur pada FSS menyebentuk disiasat. Pemodelan separuh infinit membenarkan pemodelan tatasusunan finit dan infinit masing-masing dalam arah lengkung dan tidak lengkung. Dengan menggunakan teknik ini, kesan lentur terhadap prestasi FSS yang dicadangkan pada sudut tuju normal bagi polarisasi TE and TM dapat diperolehi. Daripada keputusan yang diperolehi, gelung cincin berlingkar FSS adalah paling sensitif terhadap kesan lentur, manakala gelung cincin FSS adalah paling kurang sensitif pada kesan lentur. Semua geometri FSS yang dicadangkan difabrikasi menggunakan antara teknik fotolitografi atau cetak dakwat sembur. Prototaip yang dihasilkan diukur secara eksperimen dengan menggunakan teknik ukuran dwi-statik. Kesemua FSS yang dicadangkan menyokong pelemahan minima sebanyak -25 dB pada 10 GHz. Keputusan pengukuran menujukkan kesamaan dengan keputusan simulasi. Oleh yang demikian, FSS yang dicadangkan boleh digunakan dalam kedua-dua struktur menyatah dan menyebentuk.

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LIST OF ABBREVIATIONS

FSS	-	Frequency Selective Surface
5G	-	Fifth Generation
IoT	-	Internet of Things
VNI	-	Visual Network Index
EMI	-	Electromagnetic Interferance
ICU	-	Intensive Care Unit
CST	-	Computer Simulation Technology
TE	-	Transverse Electric
TM	-	Transverse Magnetic
FR-4	-	Fire-Retartant 4
PET	-	Polyethylene Terephthalate
CRL	-	Convoluted Ring Loop
MRL	-	Miniaturized Ring Loop
GHz	-	Giga-Herthz
HFSS	-	High Frequency Structure Simulator
FEM	-	Finite Element Method
FDTD	-	Finite-Difference Time-Domain
MoM	-	Method of Moment
ESG	-	Energy Saving Glass
RF	-	Radio-Frequency
RCS	-	Radar Cross Section
ISM	-	Industrial, Science, and Medical
UWB	-	Ultra-wideband
GSM	-	Global System for Mobile Communication
QMSIW	-	Quarter-Mode Substrate Integrated Waveguide
PCB	-	Printed-Circuit Board
VNA	-	Vector Network Analyzer

FSPL	-	Free Space Path Loss

LIST OF SYMBOLS

ε_r	-	Dielectric constant
ε_{eff}	-	Effective dielectric constant
ε_{air}	-	Dielectric constant of air
ε_{water}	-	Dielectric constant of water
Z	-	Impedance
C	-	Capacitance
H	-	Inductance
$f_{resonant}$	-	Resonant Frequency
σ	-	Conductance
σ_{Ag}	-	Conductance of Silver Nanoparticle Ink
R	-	Electrical Resistance
A_c	-	Cross-Sectional Area
L	-	Length of the conductor
λ	-	wavelength of the resonant frequency
$t_{dielectric}$	-	Thickness of the dielectric substrate
t_c	-	Thickness of the conductor
h	-	Height of the FSS Prototype
$r_{0.6}$	-	Radius of the sixth Fresnel Zone
n	-	Fresnel Zone number
L	-	Length of the conductor
d_1	-	Distance of FSS from the Transmitter
d_2	-	Distance of FSS from the Receiver
$d_{far-field}$	-	Minimum seperation of two horn antenna
D	-	Maximum dimension of the horn antenna
d	-	Seperating distance between two horn antennas
p	-	Periodicity
r_1	-	Inner radius of the ring shape FSS

r_2	-	Outer radius of the ring shape FSS
w	-	Width of the conductors
l	-	Lenght of the element
g	-	Element gap
θ	-	Angle of incidence
ρ	-	Electrical resistivity
S_{11}	-	Reflection coefficient
S_{21}	-	Transmission coefficient
c	-	speed of light
Δf_s	-	Shifting in resonance frequency

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CHAPTER 1

INTRODUCTION

1.1 Research Background

The introduction of multimedia infotainment application and smart gadgets such as smartphones, tablets, and smartwatches result in exacerbating the demand for communication data [1]. Recently, a number of researchers have been scrutinizing on the employment of Internet of Thing (IoT), machine to machine communication and device and device communication [1, 2] which has further escalated the demand for communication data. On the recent report of visual network index (VNI) from Cisco, it is expected that the worldwide mobile traffic will increase more than ten times than the contemporary figures [1]. In consequence, the fifth generation (5G) communication is contemplated to advocate a huge data transmission to overcome the mobile traffic congestion problems [2, 3]. In contemplation of realizing the vision of 5G communication, one of the proposed approaches is to utilize a smaller cell size so that the bandwidth that can be used for data transmission is escalated [4]. Although the mentioned solution manages to support higher communication data, but, it results in the exponential growth of base stations. The proliferation of the mobile base station directly or indirectly imposes the potential electromagnetic interference (EMI) risk or radiation hazard to the human life and some sensitive electronic equipment [5, 6]. In addition, the X-band frequency is widely employed for the airport radar system [7] and satellite communication [8]. These system usually utilize high power for detection purpose and create significant inteference to the other wireless devices. For instance, the intensive care unit (ICU) in the hospital that equipped with a lot of sensitive medical devices that used to support human life and the storage house for the military elements such as communication devices for military explosive materials and flammable liquid which are sensitive toward these electromagnetic radiation, Therefore, it is crucial to shield all these unwanted electromagnetic signals.

Frequency Selective Surface (FSS) is a planar periodic array structure that trumped up from either radiating or non-radiating element on top of the dielectric substrate [9]. FSS behave like a spatial filter, which only block specific frequency and transparent to other frequency signals [9] is being proposed to overcome the aforementioned problem. However, unlike microwave filters, the FSS is operating in the function of both frequency and angle of incidence as well as the electromagnetic waves polarisations [5, 9]. Consequently, FSS is commonly designed as either a bandpass or bandstop filters. Moreover, FSS is also widely employed as the antenna radome to protect the antenna [9–11], sub-reflector for antenna's performance enhancement [12, 13]and the beam switching solution for smart antenna system [14, 15]. With such extensive application of FSS, compatibility with other devices and hassle-free installation within existing building and devices come into mind. In this study, the geometry of the FSS is formulated to provide screening for X-band signals while allowing other signals to pass through it. The suggested FSS could conveniently be cascaded with existing structures and devices without interrupting other devices.

This research involves the design and development of a single band FSS to provide screening over X-band frequency. The FSS element that manages to stipulate a stable performance over TE and TM polarisation. The angular stability of the FSS is also investigated. In addition, to allow realize hassle-free installation features of the FSS, flexible and durable substrates are investigated and the fabrication techniques are identified. All the simulation of the design is performed using CST MWS commercial software. The optimised design is fabricated and tested experimentally to assure the suggested FSS able to provide sufficient shielding for X-band signals.

1.2 Problem Statement

As deliberated in the previous section, with the exponential growth of the high-end devices can prompt to various issues. The main problem is the EMI that precipitated from the mobile base station that gives significant radiation hazard to the sensitive areas such as airport, armed-forces camp, hospital and others. The electromagnetic intrusion is not only desensitized the function of the electronic system but it also can impair the security of the system [5, 16]. The traditional practice to shield the unwanted electromagnetic waves is to implement the solid metallic shield [5, 17] or reinforced walls [18, 19] on the sensitive area. However, these approaches in impractical as it is very costly and labour intensive and it blocks both useful and unwanted frequency bands.

Other alternative approaches that commonly employed in the market to overcome the EMI problem are to utilized the signal jammer [20–22]. The signal jammer where it can obstruct the unwanted signals by employed the concept of destructive interference. The signal that having the same wavelength of the unwanted frequency is being transmitted by the signal jammer to causes interference toward the unwanted frequency and hence the electromagnetic waves will be devastating [20]. However, this device is relatively costly as it required a high power supply in corresponding to the coverage area and power needed [20]. Besides that, in most of the countries like United Kingdom, Australia, and Sweden, signal jammer had been prohibited [22].

As a result, FSS which act like a spatial filter to provide screening for the unwanted frequency band be nominated as the finest solution, as it obliterated the demand of electrical power supply compare to the signal jammer. As for the metallic shield, FSS is much affordable as fewer conductors are needed to provide the attenuation with same shielding effectiveness. Besides that, FSS is more feasible in the manner that it only blocked the unwanted frequency while transparent to other useful frequency bands.

Consequently, to ensure the FSS provides the screening of the X-band frequency, FSS requires being developed with a band-stop filtering characteristic. As a result, the FSS will provide the reflective features for the unwanted frequency, which is ranging from 8 GHz to 12 GHz in this study, while allowing other electromagnetic waves to pass over it. As mentioned previously, FSS operates as a spatial filter, on that account, the electromagnetic signals travelling at the various angle of incidence with either horizontal polarized (TE) or vertically polarized (TM). On that account, it is very important to assure that the proposed geometry of the FSS manages to provide a stable transmission frequency response for both of the polarisations and both the normal and oblique angles of incidence [5]. To ensure the recommended FSS is compatible with other devices and hassle-free installation within existing building and devices, it is crucial to take the substrates that will be used for the FSS design and the fabrication technique of the FSS into the account.

1.3 Objectives

The objectives of this research are:-

1. To design an FSS geometry that manages to provide the attenuation of X-band frequency bands over planar and conformal features.
2. To fabricate the proposed FSS array cell by utilizing the conventional photolithography method and inkjet printing technique.
3. To validate experimentally the transmission frequency response of the fabricated FSS.

1.4 Scopes

The research work focused on the study of single band planar and conformal frequency selective surface that can be employed as the electromagnetic shield. The proposed single band FSS is developed to furnish screening over the X-band frequency bands which are covered from 8 GHz to 12 GHz. Since the FSS is functioned as a spatial filter, consequently, the optimized design of the FSS unit cell has to manage to provide a stable transmission coefficient at both normal and oblique angle of incidence at both TE and TM polarizations. In this research, the proposed planar FSS element is expected to provide a stable frequency response up to the angle of incidence of $60°$. In addition, the conformal FSS is expected to function as the X-band EMI shield at normal angle of incidence for TE and TM polarization when it is bent. The commercialized software CST Microwave studio is employed as the simulation tool in the design and simulation of the FSS unit cell in this study. The unit cell and open (add space) boundaries are used for simulating the designs of the planar FSS. On the other hand, the semi-infinite simulation modelling is used to examine the bending effect of the flexible FSS at normal angle of incidence. Due to the limitation of the measurement setup, the evaluation of the bending effect is limited to a cylinder radius of 150 mm and 200mm. Moreover, there are a total of two substrates are employed in this research which is FR-4 and PET substrate. The FR-4 substrate based FSS is fabricated using the conventional photolithography method whereas the PET substrate based FSS is manufactured with the help of inkjet printing technology. At the end of the research, the bi-static measurement method is utilized in the measurement of the transmission coefficient of the fabricated FSS prototype so as to validate the simulated results. Equipment such as horn antennas and vectors network analyzer is employed.

1.5 Organisation of Thesis

This thesis comprised of six chapters. The first chapter of this thesis provides the general synopsis of this research and its objectives. The scope of the study and the benefits in conducting the research are also described in this chapter.

Chapter 2 provides a comprehensive literature review on the works that had been done by the other researchers. This chapter deliberates the general features of the FSS and its filtering features. The applications of the FSS is also presented in this chapter. Besides that, the key factors that determined the performance of the FSS are reviewed. The equivalent circuit modeling is utilized to develop and analyze the FSS structure. Nevertheless, the extra merit and hindrances of other associated studies that carried out by other researchers are demonstrated.

Chapter 3 reports about the methodology of the research. This chapter provides a detail discussion about the methods or approaches that were employed to perpetuate the objectives of the research. The software used for simulation and fabrication technique employed to produce the FSS prototype are presented.

Chapter 4 discuss the preliminary study of the research which is the parametric evaluation. The parameters that manage to influence the performance of the FSS are investigated extensively.

Chapter 5 outlines a structured design technique that utilized to develop the advocated FSS. The proposed FSS is developed on FR-4 and PET substrate to provide shielding over X-band frequency. The suggested FSS geometries are fabricated using photolithography method and inkjet printing technique. The measured results and simulated results are as well, being compared in this chapter.

Lastly, Chapter 6 draws some conclusions including the findings and key contribution of the research, as well as the recommendation for future developments.

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