FREQUENCY SELECTIVE SURFACE (FSS) FOR CELLULAR SIGNALS SHIELDING

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NUR KHALIDA BINTI ABDUL KHALID

A thesis submitted in
fulfillment of the requirement for the award of the
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I hereby declare that the work in this thesis is my own except for quotations and summaries which have been duly acknowledged.

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ASSOC. PROF. DR. FAUZIAHANIM BINTI CHE SEMAN

This thesis is dedicated to my parents, for their endless love, support and encouragement.

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ABSTRACT

This thesis proposes a frequency selective surface (FSS) for interference control causes by the proliferation of mobile devices. FSS is a periodic structure etched on a dielectric substrate which acts as a spatial filter. The proposed FSS is designed as a band-stop filter to attenuate the cellular signals operating at GSM900, GSM1800 and IMT2000 frequency bands. The employment of the FSS is an effective shielding technique as it eliminates the need for power supply and prevents the use of mobile phone without disrupting other types of communications. All the designs and simulations are done using the Computer Simulation Technology (CST) Microwave Studio software. There are three main groups of the FSS prototype designed in this study. The first group of the FSS prototype is etched on FR-4 substrate using the photolithography technique. On the other hand, the second group of the FSS prototype is printed on glossy paper substrate using the manual fabrication and inkjet printing techniques. These two techniques are implemented using the conductive silver pen and copper nanoparticle ink, respectively. The simulated results of the conventional square loop FSS printed on paper shows a good angular stability compared to the conventional square loop FSS printed on FR-4 substrate. The utilization of the inkjet printing technique is proposed in order to overcome the limitations of the manual fabrication technique. In order to transform a non-conductive printed pattern to a conductive one, the printed FSS element has to undergo the post-processing, called sintering. This consequently leads to a final prototype of the FSS printed on polyimide film. In order to validate the simulated results experimentally, the measurement is performed inside the anechoic chamber. The measured and simulated results are shown to be in a very good agreement with each other. FSS printed on glossy paper is highly recommended due to its very low cost and environmental-friendly material.

ABSTRAK

Tesis ini mencadangkan aplikasi permukaan frekuensi terpilih (FSS) untuk mengawal gangguan yang disebabkan oleh peningkatan penggunaan telefon mudah alih. FSS adalah struktur berkala yang dicetak pada substrat dielektrik yang bertindak sebagai penapis spatial. FSS yang dicadangkan direka sebagai penapis jalur-berhenti untuk melemahkan isyarat telefon mudah alih yang beroperasi pada GSM900, GSM1800 dan IMT2000 jalur frekuensi. Pengaplikasian FSS adalah satu teknik perlindungan yang berkesaan kerana ia tidak memerlukan bekalan kuasa untuk beroperasi dan menghalang penggunaan telefon bimbit tanpa mengganggu aktiviti komunikasi yang lain. Kesemua rekaan dan simulasi dilakukan dengan menggunakan perisian *Computer Simulation Technology* (CST). Terdapat tiga kumpulan utama prototaip FSS yang direka dalam kajian ini. Kumpulan pertama prototaip FSS dicetak pada substrat FR-4 menggunakan teknik fotolitografi. Sebaliknya, kumpulan kedua prototaip FSS dicetak pada kertas berkilat menggunakan teknik fabrikasi manual dan percetakan inkjet. Teknik fabrikasi manual telah dilaksanakan menggunakan pen perak konduktif, manakala, teknik percetakan inkjet dilakukan mengunakan dakwat nanopartikel tembaga. Keputusan simulasi gelung persegi FSS yang dicetak pada kertas menunjukkan kestabilan sudut yang lebih baik berbanding dengan gelung persegi FSS yang dicetak pada substrat FR-4. Penggunaan teknik percetakan inkjet adalah dicadangkan bagi mengatasi limitasi teknik fabrikasi manual. Bagi mengubah ciri elemen FSS daripada bukan-konduktif kepada konduktif, elemen FSS yang dicetak perlu menjalani pasca-pemprosesan yang dikenali sebagai pensinteran. Ini seterusnya membawa kepada prototaip FSS yang terakhir yang dicetak pada filem poliimida. Bagi mengesahkan hasil simulasi komputer, pengukuran telah dijalankan di dalam *anechoic chamber*. Hasil pengukuran yang didapati adalah konsisten dengan hasil simulasi komputer. FSS yang dicetak pada kertas berkilat adalah amat disyorkan kerana kosnya yang sangat rendah dan bahannya yang mesra alam.

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LIST OF SYMBOLS AND ABBREVIATIONS

ε_r	-	Dielectric constant
ε_{eff}	-	Effective dielectric constant
θ	-	Angle of incidence
λ	-	Wavelength of the radio wave
ρ	-	Electrical resistivity
σ	-	Electrical conductivity
Δf_r	-	Shift in resonance frequency
A_c	-	Cross sectional area
C	-	Capacitance
c	-	Speed of light
D	-	Physical length of the antenna
d	-	Distance from the transmitter to the receiver
d_1	-	Distance from the transmitter to the FSS
d_2	-	Distance from the receiver to the FSS
f	-	Length of the slot
f_l	-	Lower frequency at -10 dB
f_r		Resonance frequency
f_u	-	Upper frequency at -10 dB
g	-	Gap between the substrate and the element
g_1	-	Gap between the substrate and the outer element
g_2	-	Gap between the outer and inner elements
h	-	Height of the FSS
L	-	Inductance
l	-	Length of the element
l_s	-	Length of the substrate
l_1	-	Length of the outer element

l_2	-	Length of the inner element
N_2	-	Nitrogen
R	-	Resistance
$r_{0.6}$	-	Radius of the 6^{th} Fresnel Zone
r_1	-	Radius of the outer element
r_2	-	Radius of the inner element
s	-	Width of the slot
S_{11}	-	Reflection coefficient
S_{21}	-	Transmission coefficient
t	-	Thickness of the substrate
t_c	-	Thickness of the copper
w	-	Width of the element
w_1	-	Width of the outer element
w_2	-	Width of the inner element
CST	-	Computer Simulation Technology
DMP	-	Dimatix Materials Printer
FDTD	-	Finite-Different Time-Domain
FEM	-	Finite Element Method
FESEM	-	Field Emission Scanning Electron Microscopy
FSPL	-	Free Space Path Loss
FSS	-	Frequency Selective Surface
IPL	-	Intense Pulsed Light
IR	-	Infrared
MCMC	-	Malaysian Communications and Multimedia Commission
MoM	-	Method of Moment
PCB	-	Printed Circuit Board
RF	-	Radio Frequency
TE	-	Transverse Electric
TM	-	Transverse Magnetic
UV	-	Ultraviolet
WLAN	-	Wireless Local Area Network

LIST OF APPENDICES

LIST OF PUBLICATIONS

Journal:

(i) N. K. Khalid and F. C. Seman, "Double square loop Frequency Selective Surface (FSS) for GSM shielding," *Australian Journal of Basic and Applied Sciences (AENSI)*, pp. 25-29, Dec. 2014.

Proceedings:

(i) N. K. Khalid and F. C. Seman, "Characterisation of Electrical Conductivity of Silver Printed FSS for Cellular Signals Suppression," in *2015 IEEE International RF and Microwave Conference (RFM)*, December 2015.

(ii) F. C. Seman and N. K. Khalid, "Design strategy for optimum planar square loop FSS with different dielectric substrates," in *Applied Electromagnetic International Conference (APPEIC)*, vol. 344, pp.87-94, December 2014.

(iii) F. C. Seman and N. K. Khalid, "Double square loop FSS with slots for closer band spacing at oblique incidence," in *2014 IEEE Asia-Pacific Conference on Applied Electromagnetics (APACE)*, pp. 195-198, December 2014.

(iv) F. C. Seman and N. K. Khalid, "Investigations on fractal square loop FSS at oblique incidence for GSM applications," in *7th Electrical Power, Electronics, Communications, Control and Informatics International Seminar (EECCIS)*, pp. 62-66, August 2014.

(v) N. K. Khalid and F. C. Seman, “Double square loop Frequency Selective Surface (FSS) for GSM shielding,” in *International Conference on Communication and Computer Engineering (ICOCOE)*, vol. 315, pp. 223-229, May 2014.

LIST OF AWARDS

(i) **Silver Medal in Malaysia Technology Expo [MTE 2014]:**
F. C. Seman and N. K. Khalid, "Wallpaper Frequency Selective Surface for GSM Shielding."

(ii) **Silver Medal in Research and Innovation Festival [R&I 2013]:**
F. C. Seman and N. K. Khalid, "Wallpaper Frequency Selective Surface for GSM Shielding."

INTELLECTUAL PROPERTY

(i) **Patent**
F. C. Seman and N. K. Khalid, "Wallpaper Frequency Selective Surface for Microwave Signal Shielding." (Patent Pending)

CHAPTER 1

INTRODUCTION

1.1 Overview

In recent years, there has been immense growth in the number of application of wireless technologies, including wireless local area networks (WLANs) and mobile systems. The explosive growth of mobile systems is due to its function as more than just a communication device. For instance, in most developed countries, mobile phones have been used for variety of purposes such as business dealings, mobile banking services, tracking system and personal use. However, there is concern that mobile phone radiation may cause serious problems related to an electromagnetic interference [1]-[2]. Therefore, frequency selective surface (FSS) is proposed in this study in order to overcome the aforementioned problems.

Generally, FSS is an array of periodic metallic patches or its complement metallic apertures, etched on a dielectric substrate. It can be designed to transmit or reflect the signals at the target resonance frequency [3]. FSSs have been extensively used for decades in various applications such as dichroic reflectors [4]-[6], antenna radomes [7]-[10] and spatial filters [11]-[14]. There is a large volume of published studies describing the function of the FSS as the band-pass [14]-[16] or band-stop filters [17]-[19]. The frequency bands for mobile services in Malaysia as provided by the Malaysian Communications and Multimedia Commission (MCMC) are GSM900, GSM1800 and IMT2000 [20]. Thus, the structure of the FSS is designed to attenuate signals at these three frequency bands while transmitting other signals. The proposed FSS could easily be employed in any building that wants to prevent the use of mobile phone without disrupting other types of communication.

1.2 Problem Statements

As previously explained, the proliferation of mobile devices can lead to numerous problems. This includes an interference of the widely used mobile signals with the highly sensitive equipment employed in the buildings such as hospitals, airports, military camp and so forth. Interference not only can degrade the system's performance but it also can harm the security of the system [1]. Besides, the noise caused by the use of mobile phones at improper place and time can contribute to a huge social problem [21].

Currently, in the market there are few approaches that can be used to overcome those problems. The first approach is the mobile phone jammer where it can block the mobile signals by sending out radio waves along the same frequencies that the mobile phones use, which causes interference between the mobile phone and the mobile base station. This normally consists of basic electronic components including voltage controlled oscillator, tuning circuit, noise generator, RF amplifier and the most significant part is the power supply [22]. Besides, there are various types of mobile phone jammer that can control the operation radius of the jammer. Larger operation radius of mobile phone jammer requires more power to operate [22]. This will contribute to higher costs which will then affect long term utilities.

Another better option that is more environmental friendly is a shielding paint technique. By implementing this technique, the wall of the restricted area can be painted using lossy shielding paint which will eventually absorbs all the signals passing through the wall regardless of their origin [23]. Hence, this technique is against the operation of the jammer where the objective is only to disrupt the mobile signals and allows other frequencies to pass through the wall.

Therefore, the employment of the FSS that is able to attenuate the mobile signals becomes the best option, as it eliminates the need for power supply which will certainly help in reducing operational costs. To compare with the shielding paint technique, FSS is more practical as it allows other signals to pass through the wall. This concept has been applied in the construction of multi-resonance Salisbury screen absorber [24].

In order to provide shielding for mobile signals, FSS needs to be designed to act as a band-stop filter. By doing this, the FSS will show reflective properties at the resonance frequencies and transmit other frequencies. Besides, the bandwidth requirement of each frequency band provided by the MCMC needs to be fulfilled. Since FSS behaves as a spatial filter, the incoming signals may hit the FSS surface from any arbitrary angle with different polarizations. Therefore, it is very crucial to design the FSS that has a stable frequency response for normal and oblique angles of incidence for both TE (electrical field perpendicular to the plane of incidence) and TM (magnetic field perpendicular to the plane of incidence) polarizations [3].

1.3 Objectives

The objectives of the study are to:

1. Design unit cell of the FSS that is able to attenuate the mobile signals at the specified frequency bands
2. Realize deposition of metallic FSS on different types of the dielectric substrate
3. Validate the simulated results of the FSS experimentally

1.4 Scope of the Study

1. FSS is designed to attenuate signals at GSM900, GSM1800 and IMT2000 frequency bands. It includes bandwidth for both lower and upper bands of each frequency band as shown in Table 1.1.

Table 1.1: Spectrum allocation list for mobile services in Malaysia [20]

Frequency Band	Lower Band (MHz)	Upper Band (MHz)
GSM900	880-915	925-960
GSM1800	1710-1785	1805-1880
IMT2000	1920-2010	2110-2200

2. The optimized structure of the FSS should have stable frequency response under various angles of incidence for both TE and TM polarizations. Angle of incidence in this study is limited up to 45°.

3. The designs and simulations in this study are done using the Computer Simulation Technology (CST) Microwave Studio software. Frequency domain solver in CST is used to simulate the designs of the FSS.
4. There are three different fabrication techniques that are implemented throughout this study which are the photolithography, manual fabrication and inkjet printing techniques.
5. The simulated results are verified experimentally inside the anechoic chamber by employing the bi-static measurement technique. Equipment such as horn antennas and vectors network analyzer is used.

1.5 Outline of the Thesis

This thesis consists of seven chapters. The first chapter of this thesis introduced the overview of the study and its objectives. It also described about the scope of the study.

Chapter 2 is the literature review. This chapter discusses about the general background of frequency selective surfaces (FSS) and its filter characteristics. The key factors that can greatly influence the FSS performance are explained. A method that is used to design and analyze the FSS which is known as the equivalent circuit method is reviewed. Moreover, the advantages and limitations of other related studies done by other researchers are presented.

Chapter 3 describes the methodology of the study. It explains in more details about the methods or approaches that are used in order to accomplish the objectives of the study.

Chapter 4 presents the first stage of the research which is the parametric study. This study involves a comprehensive investigation of different types of the FSS element and their sensitivity at various angles of incidence and polarizations. Besides, other design parameters that can affect the frequency response of the FSS are examined.

Chapter 5 outlines a systematic design strategy that can be used to design the proposed FSS. Besides, several prototypes that are designed on FR-4 substrate such as single-band, dual-band and tri-band FSSs are presented. Comparisons between the simulated and measured results are discussed in more details in this chapter.

Chapter 6 focuses on examining the performances of the FSS deposited on two different types of the substrate. The frequency response of the FSS printed on glossy paper sheets using the commercial conductive silver pen and copper nanoparticle ink is studied. The utilization of manual fabrication and inkjet printing techniques is presented. Besides, the performance of the FSS printed on polyimide substrate using the copper nanoparticle ink is observed.

Finally, the last chapter describes the conclusion of the study and suggests directions for future developments.

Figure 1.1 summarizes the development of FSS prototypes throughout this study.

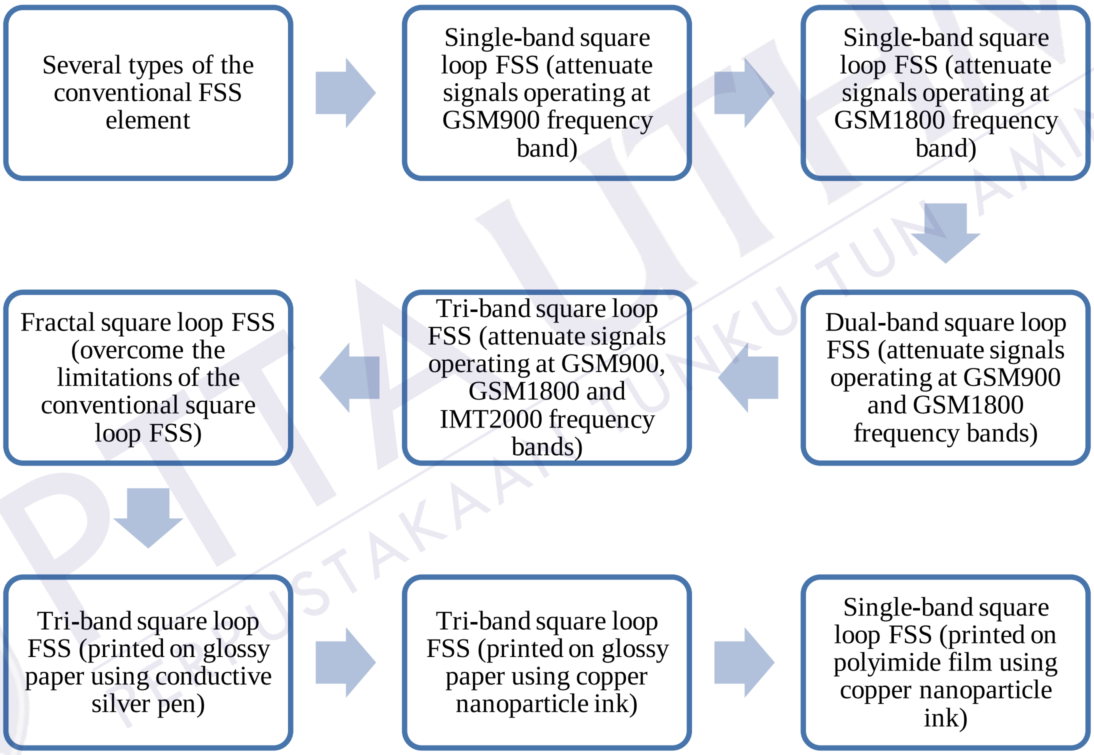


Figure1.1: Development of FSS prototypes

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter discusses about the general background of frequency selective surface (FSS) and its filter characteristics. Besides, the effects of FSS element geometry, conductivity of the element and properties of the dielectric substrate on frequency response of the FSS will be described. The bandwidth requirements of each frequency band provided by the Malaysian Communications and Multimedia Commission (MCMC) will be summarized. In addition, an equivalent circuit method that is used to design and analyze the FSS will be explained. At the end of this chapter, the advantages and limitations of other related studies done by other researchers in various applications of the FSS will be compared.

2.2 General Background of FSS

FSS is a periodic array of metallic patches or its complement metallic apertures, etched on a dielectric substrate, which acts as a spatial filter [3]. Filter characteristics of the FSS are mainly dependent on the surface's element pattern.

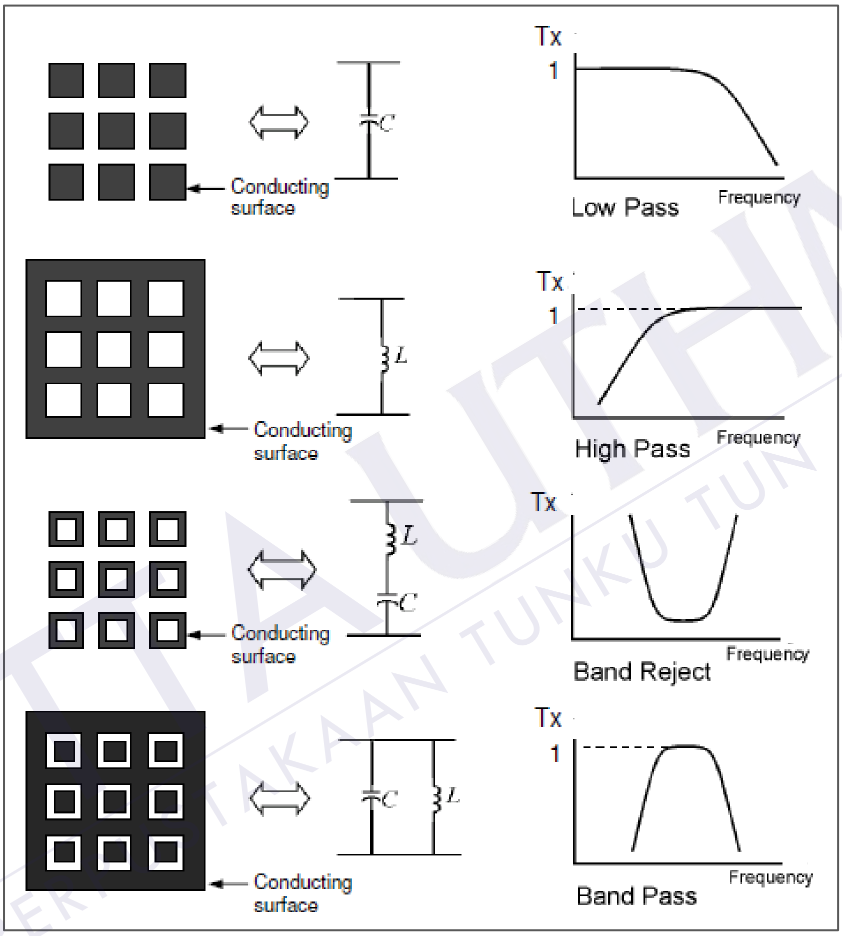


Figure 2.1: Filter responses of the FSS [28]

Thus, by adjusting the pattern of the element, FSS can be designed as a low-pass, high-pass, band-pass or band-stop filters, as shown in Figure 2.1. The patch element group consists of both band-stop and low-pass FSSs, whereas band-pass and high-pass FSSs belong to the aperture or slot group.

Depending on the applications, there are cases where the signals need to be confined or amplified [13]. For instance, a band-pass FSS is deposited on the energy-saving glass to overcome its limitation. This glass is primarily designed to block the infrared (IR) rays. However, the problem arises due to the presence of the metallic oxide coating as it is not only attenuates the infrared waves, but it also attenuates many other useful microwave signals. By deploying the FSS on this glass, the transmission of useful signals can be improved while still maintaining IR attenuation as much as possible [14], [26]. Besides, a band-pass FSS is also utilized to enhance the wireless local area network (WLAN) signals in WLAN device [15]. In contrast, in [17]-[18], the authors proposed the deployment of the FSS as the band-stop filter. G. H. H. Sung *et al*. attached a band-stop FSS as a cover on the wall surface in order to reject the signals operating at 5.4 to 6.4 GHz [18]. This signal confinement can improve the security of the system and reduce the interference level [13]. Besides, E. A. Parker *et al*. designed the FSS that can provide both pass-band at about 400 MHz and isolation of the signals above 600 MHz simultaneously [27]. In this study, FSS will be designed as a band-stop filter in order to attenuate signals at GSM900, GSM1800 and IMT2000 frequency bands and allow other signals to pass through the wall.

In order to ensure that the proposed FSS is capable to provide superior performances, there are several factors that need to be taken into account when designing the FSS. This includes FSS element geometry, conductivity of the FSS element and properties of the dielectric substrate. Each factor will be described in more details below.

2.2.1 FSS Element Geometry

One of the important factors that can influence the frequency response of the FSS is the FSS element geometry. FSS element is not only limited to square shape as illustrated in Figure 2.1, but it is also can be designed as circular, hexagon or more convoluted shapes.

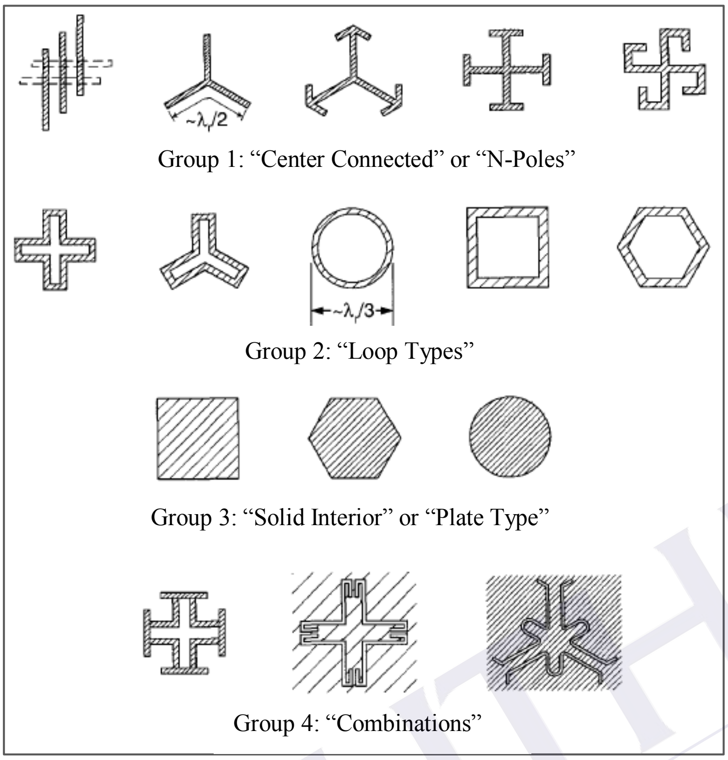


Figure 2.2: The four major groups of element-type [28]

In general, FSS has four major groups of element-type, which are center connected, loop types, solid interior or plate types and combinations, as shown in Figure 2.2. Each group of elements offers different performances in terms of the angular stability, cross-polarization, bandwidth and band separation [29]. Therefore, it is very crucial to choose the FSS element that meets all the requirements needed for that particular application.

In terms of the bandwidth, the first group, which is the center connected elements such as dipoles, tripoles, Jerusalem crosses and cross dipoles are categorized as the most narrow-banded elements. On the other hand, the second group which is the loop elements, for instance, square loop, hexagon loop and circular loop generally offer a good bandwidth performance [28]. Since loop elements mostly have small x and y dimensions, it can be spaced close to one another [28]. Therefore, this type of element is very suitable to design a multi-band FSS.

On the other hand, solid interior or plate elements have undesirable characteristics. First, it is very hard to achieve resonance for this type of elements as they are highly inductive elements with small capacitances between them [28]. Second, these elements cannot be placed close to one another as their x- and y- dimensions are around a half of a wavelength, which prohibit them to have more than one band [28].

T. K. Wu as demonstrated in Table 2.1 summarizes some common FSS element shapes and their own distinctive characteristics. From the table, it can be seen that the square loop element shows the best performance in all aspects compared to other types of the conventional element.

Table 2.1: Performances of some common FSS element shapes [29]

Element Type	**Angular Stability**	**Cross-polarization Level**	**Larger Bandwidth**	**Small Band Separation**
Loaded dipole	1	2	1	1
Jerusalem cross	2	3	2	2
Rings	1	2	1	1
Tri-pole	3	3	3	2
Cross dipole	3	3	3	3
Square loop	1	1	1	1
Dipole	4	1	4	1

Rating: best=1, second best=2, etc.

In recent years, there has been an increasing interest in convoluting and miniaturizing the FSS element [11], [30]-[31]. By doing this, the unit cell size of the FSS can be greatly reduced, which will be tremendously useful for the practical application where the space is very limited [30]. Previous studies have shown that a higher packing density of the FSS can improve the angular stability of the FSS and overcome the grating lobe problem [32]. However, the bandwidth of the convoluted FSS is lower than other conventional elements such as square loop and circular loop [11]. The performances of some common FSS elements in terms of the bandwidth and stability with respect to different polarizations and incident angles will be investigated in Chapter 4.

2.2.2 Conductivity of the Element

It is very essential to use the FSS element with high conductivity in order to ensure that the designed FSS is capable to tune the target resonance frequency. This is due to the fact that the element with low conductivity will degrade the FSS performances. Besides, if the material with extremely small conductivity is used as the FSS element, the structure will no longer behave as a frequency selective but it will act like a common dielectric plate [26].

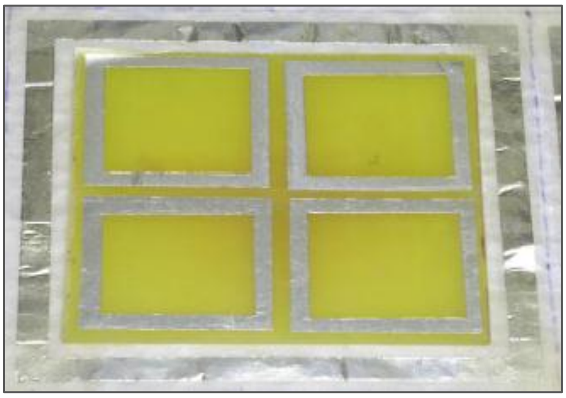


Figure 2.3: Aluminum foil pasted on the dielectric substrate [2]

In addition, the conductive material needs to be selected properly as different fabrication techniques are required if different conductive materials are used [25]. For instance, in [1]-[2], authors used the aluminum foil to design the FSS element, as illustrated in Figure 2.3. These elements are pasted on the substrate using the adhesive tape. Although this type of the fabrication technique is cheap, it is time and labor consuming [1]. Thus, this technique is not very suitable for large scale applications.

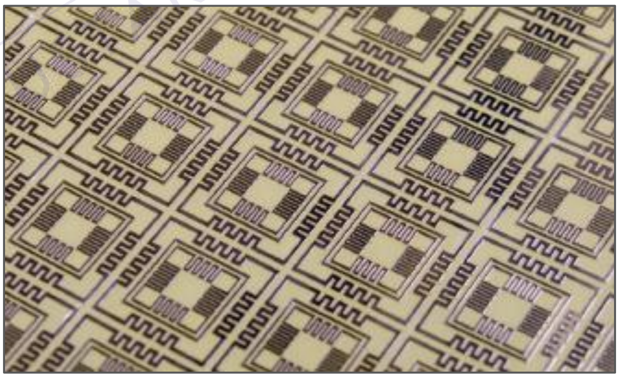


Figure 2.4: Fabricated FSS using photolithography technique [21]

The most common fabrication technique that has been widely used is the photolithography technique, which involves multiple steps such as film laminating, UV exposure, developing, etching and stripping. One of the drawbacks of this technique is that the choice of the substrates is limited since the solvent used in the etching process is corrosive [33]. Usually, copper or aluminum will be used as the conductive material as the price is reasonable. Figure 2.4 shows the fabricated FSS using this type of the fabrication technique.

An alternative of the above-mentioned conventional fabrication technique is the printing technique which can be performed by utilizing the inkjet printer and conductive ink. This technique is more environmental friendly as it can diminish high volumes of chemical waste generated through the photolithography process [34]. There are two important factors that need to be considered when applying this technique which are the ink properties and the settings of the printing system itself [33]. In this study, three fabrication techniques which are the photolithography, manual fabrication and inkjet printing techniques will be implemented. Each technique will be discussed in more details in Chapter 3.

2.2.3 Dielectric Substrate

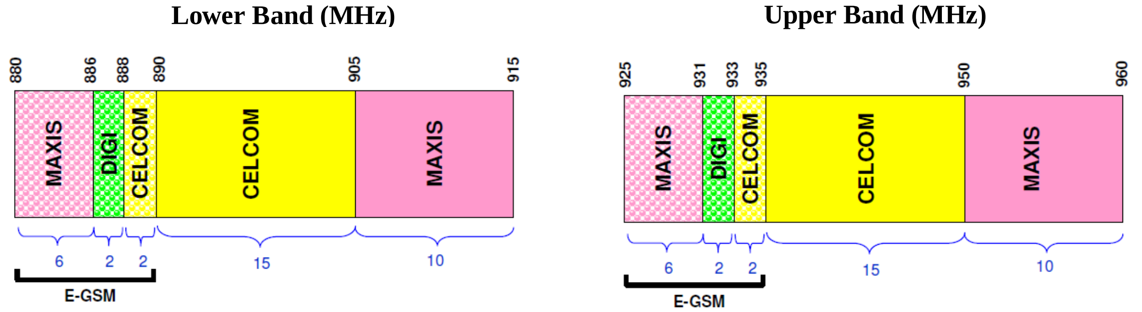
Dielectrics are mainly used to provide structural support of the FSS. Besides, this dielectric can also be used to improve the angular stability of the FSS over a range of angles of incidence [35]. However, by adding the dielectric on the FSS, the resonance frequency will be reduced [3]. Thus, it is very crucial to take into consideration the properties of the dielectric when designing the FSS. In general, the resonance frequency will be reduced by a factor of $\sqrt{\varepsilon_{eff}}$. The value of the effective dielectric constant, ε_{eff} is dependent on the arrangement of the FSS element and the thickness of the dielectric substrate itself. FSS element can be attached at one side of the dielectric substrate or embedded in between the dielectric substrates [25]. The dielectric substrate is considered thick if the thickness is greater than 0.05 electrical wavelengths [28]. Table 2.2 lists different values of ε_{eff} depending on the substrate thickness and the arrangement of the FSS element.

Table 2.2: Different values of the effective dielectric constant [28]

Dielectric Substrate Thickness	FSS Element Attached at One Side of the Dielectric Substrate	FSS Element Embedded in between the Dielectric Substrates
> 0.05 electrical wavelengths	$\varepsilon_{eff} = (\varepsilon_r + 1)/2$	$\varepsilon_{eff} = \varepsilon_r$
≤ 0.05 electrical wavelengths	ε_{eff} is a nonlinear function of the dielectric substrate thickness	

2.3 Spectrum Allocation for Mobile Service in Malaysia

In order to ensure that the proposed FSS can effectively attenuate the mobile signals, the spectrum allocation list for mobile services provided by the MCMC is used as the guidelines. Spectrum allocation for each frequency band is shown in more details in Figure 2.5. From the figure, it can be seen that there are several mobile operators that are available in Malaysia such as Maxis, Digi, Celcom and U-Mobile.



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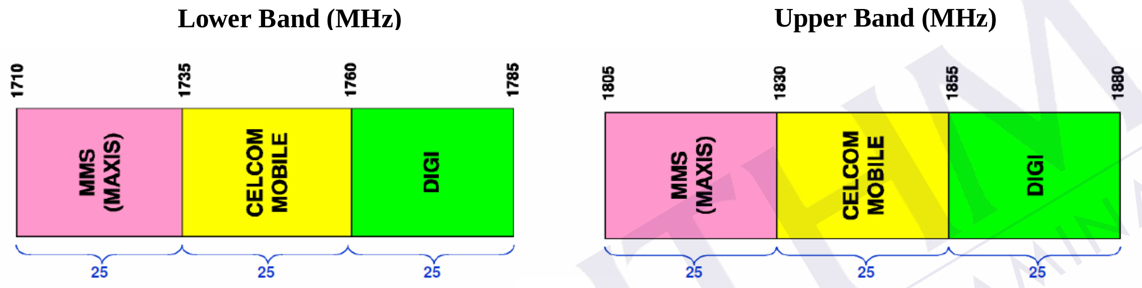

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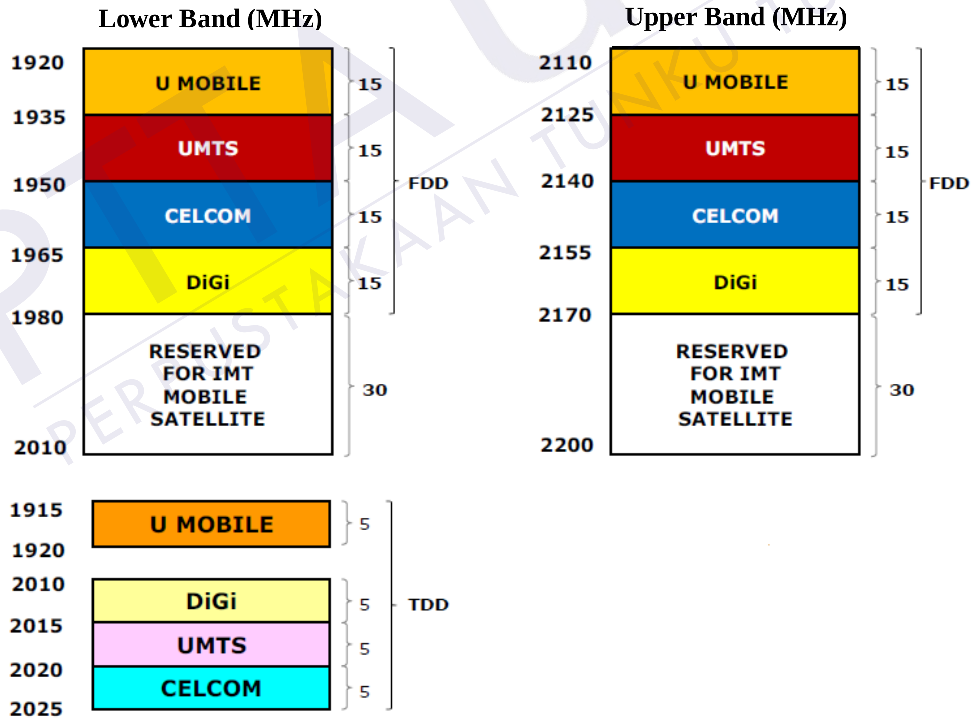


(c)

Figure 2.5: Spectrum allocation for (a) GSM900 (b) GSM1800 and (c) IMT2000 frequency bands [20]

The bandwidth is calculated according to Equation 2.1 [36].

$$Bandwidth = (\frac{f_u - f_l}{f_r}) \times 100\% \quad (2.1)$$

where,

f_u : upper frequency at -10 dB

f_l : lower frequency at -10 dB

f_r : resonance frequency

The -10 dB attenuation is the minimum attenuation that is required in order to reflect the signals. By improving the attenuation of the signals, the performances of the FSS can be further improved [36].

Table 2.3 summarizes the bandwidth for the lower and upper bands of all three frequency bands. FSS needs to be designed appropriately in order to ensure that the bandwidth requirement provided by the MCMC can be fulfilled.

Table 2.3: Spectrum allocation list and bandwidth for mobile services in Malaysia [20]

Frequency Band	Lower Band (MHz)	Bandwidth for the Lower Band (MHz)	Upper Band (MHz)	Bandwidth for the Upper Band (MHz)
GSM900	880-915	35	925-960	35
GSM1800	1710-1785	75	1805-1880	75
IMT2000	1920-2010	90	2110-2200	90

2.4 Equivalent Circuit Model of FSS

In general, there are various techniques that can be used to design and analyze the FSS. The most commonly used techniques are the numerical calculation method and the equivalent circuit model. The numerical calculation method includes method of moment (MoM), finite element method (FEM) and finite-difference time-domain (FDTD) method. These methods can be used to obtain precise data of S matrices and the distributions of electric fields [37]. However, these methods consume more time and require powerful computational facilities to implement [38]. Moreover, by utilizing these methods, the designers tend to ignore the inner relationship between the physical structure and the frequency response [37].

As a solution to the above-mentioned problems, the equivalent circuit models can be used as an alternative method to analyze the FSS. This method is relatively simple and fast [39]. Many studies have successfully employed this approach for different element geometries such as square loop, dipoles and Jerusalem cross [40]-[42]. By implementing this method, FSS can be represented as an inductor-capacitor circuit model. Although it is not as accurate as the other methods, this model can be used to investigate the electrical principles behind the parameter adjustment of the FSS.

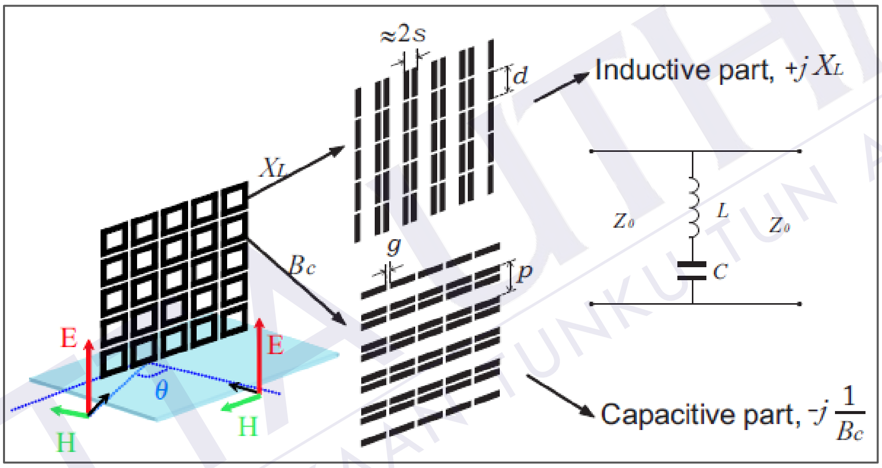


Figure 2.6: An equivalent-circuit model for the single-band square loop FSS [25]

For instance, G. H. H. Sung *et al*. modeled their proposed square loop FSS by an equivalent circuit, in which an inductive element, L is in series with a capacitive element, C as illustrated in Figure 2.6 [1]. The relationship between the resonance frequency and the values of the inductance and capacitance is expressed by Equation 2.2 [40].

$$f_r = 1/2\pi\sqrt{LC} \tag{2.2}$$

Equation 2.2 demonstrates that the resonance frequency is inversely proportional to the values of inductance and capacitance. The inductive impedance in the equivalent circuit is contributed by the vertical side of the element whereas the horizontal side of the element contributes to the conductive impedance [1]. Consequently, a longer side length is required in order to tune a lower resonance frequency. In addition, by adjusting the values of L and C, the bandwidth of the designed FSS can be further optimized, as the bandwidth is directly proportional to the value of the inductance and inversely proportional to the capacitance value, as expressed by Equation 2.3 [40].

$$Bandwidth \propto \sqrt{L/C} \tag{2.3}$$

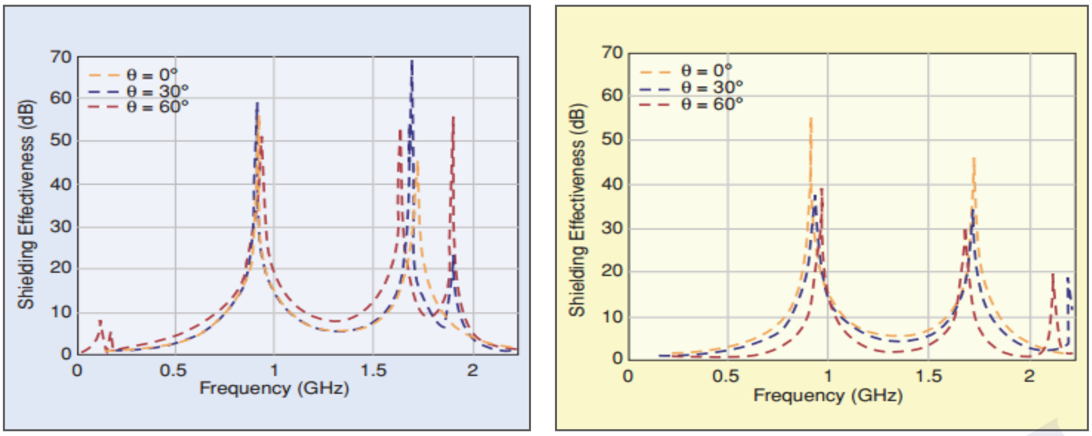
Detailed explanations and formulations of the equivalent circuit model will be presented in Chapter 5.

2.5 Previous Studies

Frequency selective surfaces (FSSs) have been extensively used for decades in various applications such as dichroic reflectors [4]-[6], antenna radomes [7]-[10] and spatial filters [1]-[3]. For spatial filter applications, FSS is widely used for mobile applications, indoor environments and energy-saving glass, which will be discussed in more details below.

2.5.1 FSS for Mobile Applications

In [3], double square loop (DSL) and double ring (DR) patch elements are designed separately in order to compare their performances. Both FSS structures are designed to attenuate GSM signals at 900 MHz and 1800 MHz. In this study, the effect of varying the relative permittivity of the substrate is studied. Based on the results obtained, it can be seen that the resonance frequency decreases as the relative permittivity of the dielectric increases. This finding shows a good agreement with the theoretical concept of the FSS that has been discussed in Section 2.2.3. Besides, it can be seen that the loading effect of the dielectric for the double ring patch element is greater than the double square loop patch element.



(a) (b)

Figure 2.7: Shielding effectiveness of the double square loop patch element for (a) TE and (b) TM polarizations under various angles of incidence [3]

Figure 2.7 shows that as the angle of incidence increases, new resonance occurs at the frequency of interest, which is known as the grating lobe. According to T. K. Wu [29], this problem arises when the electrical length of the structure increases to more than one-half of the free space wavelength. Moreover, it can be noted here that for TE polarization, the bandwidth increases as the angle of incidence increases. In contrast, for TM polarization, the bandwidth decreases with the increment of the incident angles.

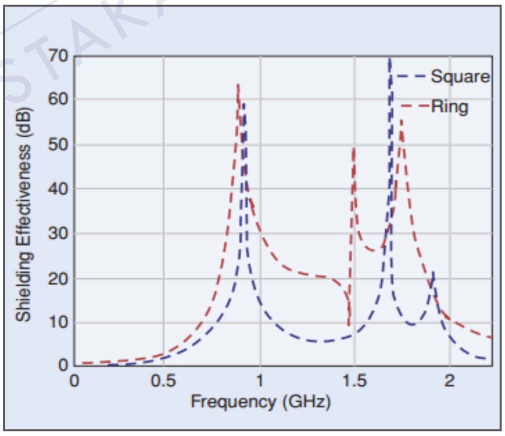


Figure 2.8: Shielding effectiveness of the double square loop and double ring patch elements for TE polarizations at θ=30° [3]

Figure 2.8 demonstrates that the double square loop patch element shows a better performance compared to the double ring patch element in terms of the angular stability.

Figure 2.9: Prototype of the wallpaper FSS [2]

Similarly, W. Kiermeier and E. Biebl introduce a new FSS element with dual-band-stop behavior at GSM900 and GSM1800 frequency bands [2]. Figure 2.9 illustrates the prototype of the wallpaper FSS, in which the periodic arrays of the FSS are fabricated using the aluminum foil. As previously discussed in Section 2.2.2, this type of the fabrication technique is not suitable for mass production as it is labor intensive and time consuming. Besides, this paper also investigates about the performances of the wallpaper FSS when it is attached to the wood (ε_r= 1.8) or glass (ε_r= 5.0). Due to the permittivity of the glass that is higher, the targeted resonance frequency for the glass decreases slightly compared to the case where the FSS is mounted on the wood.

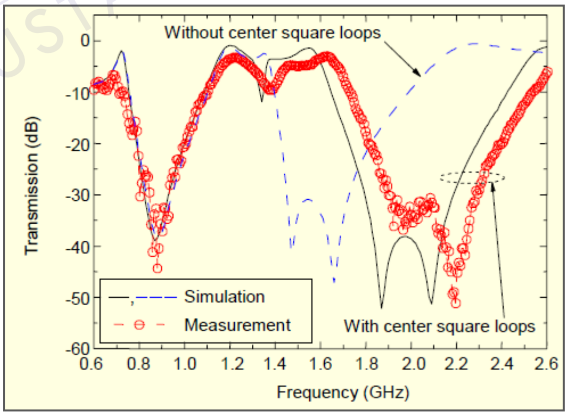


Figure 2.10: Simulated and measured transmission frequency response of the FSS at normal incidence with and without the center square loop [21]

On the other hand, in [21], the authors propose a compact FSS element in order to block mobile signals operating at Korean Cellular (824-894 MHz), PCS (1750-1870 MHz) and IMT-2000 (1920-2170 MHz) frequency bands. The proposed FSS are printed on the top and bottom sides of the pair-glass panel. Since the PCS and IMT-2000 frequency bands are separated by just 50 MHz, these two bands are combined together as one wide band. First and foremost, only the outer and inner loops with meander lines are designed. However, this design only can cover the first band, which leads the authors to introduce a center square loop in between the outer and inner square loops. Figure 2.10 shows the simulated and measured transmission frequency response of the FSS at normal incidence with and without the center square loop. It can be seen that if the center square loop is inserted, the FSS structure is capable to attenuate all three required frequency bands.

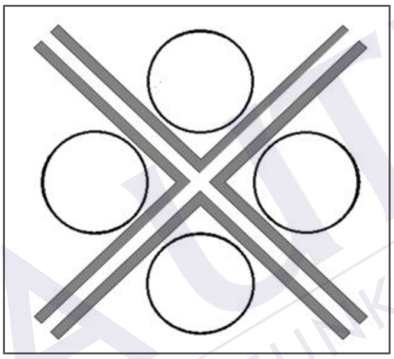


Figure 2.11: Unit cell geometry of the cross like design (CLD) FSS [43]

In contrast, R. Sivasamy *et* al. in [43], propose a distinctive FSS element to attenuate mobile signals operating at GSM1800 frequency band. Figure 2.11 demonstrates the unit cell of the cross like design (CLD) FSS that has been proposed. Since the geometry of the FSS is symmetrical, the frequency response for both TE and TM polarization at normal incidence is identical. The frequency response of the designed FSS is fairly stable under various angles of incidence. Besides, measurement is carried out inside the anechoic chamber in order to validate the simulated results. The measured results show a good agreement with the simulated results at normal incidence.

Table 2.4: Comparison of the previous studies for mobile applications

Authors	Title	Advantages	Limitations
E. Unal *et al*. [3]	Effective electromagnetic shielding	- dual-band stop behavior - compare DSL and DR patch elements fairly	- not verified experimentally
W. Kiermeir and E. Biebl [2]	New dual-band frequency selective surfaces for GSM shielding	- dual-band stop behavior - introduce a new FSS element	- time consuming and labor intensive fabrication technique
D. Kim *et al*. [21]	Compact spatial triple-band-stop filter for cellular/PCS/IMT-2000 systems	- triple-band stop behavior	- print FSS elements on both sides of the substrate
R. Sivasamy *et al.* [43]	A novel shield for GSM 1800 MHz band using frequency selective surface	- good stability under various incident angles - good agreement between measured and simulated results at normal incidence	- single-band stop behavior only
N. K. Khalid and F. C. Seman	**Frequency selective surface for cellular signals shielding**	**- tri-band stop behavior (GSM900, GSM1800 and IMT2000 frequency bands) - good stability under various angles of incidence - the simulated results are verified experimentally - copper nanoparticle ink is utilized by using an inkjet printing technique**	**- requires post-processing, called sintering**

Table 2.4 summarizes previous studies of the FSS for mobile applications and their limitations.

2.5.2 FSS in Indoor Environments

G. H. H. Sung *et al.* in [1] modify the indoor wireless physical propagation environment by attaching a square loop FSS as a cover on the wall surface. FSS structure is designed to filter out signals operating at 5.4-6.0 GHz.

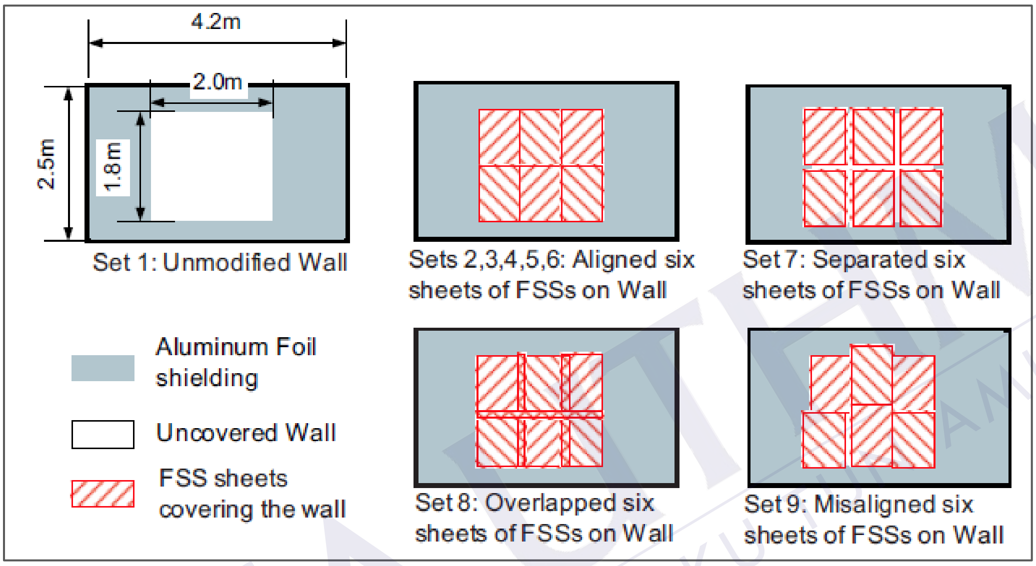


Figure 2.12: Layout of the FSS cover for nine different propagation scenarios [25]

This paper addresses about the practical application issues such as the effect of FSS misalignments on the wall and the angular stability of the FSS. For instance, nine different propagation scenarios are considered during the measurement, as illustrated in Figure 2.12. The results show that the proposed FSS is capable to provide a stable performance under various incident angles in both the azimuth and elevation planes. Besides, it is found that the overall performance of the FSS does not really change if the wall is covered with up to 3% imperfection due to misalignments and overlapping.

Similarly, M. Raspopoulos and S. Stavrou in [13] use a square loop as the FSS element. However, this paper studies the effect of deploying FSS in an indoor environment using a 3D ray tracing model. This technique can be used to predict radio propagation in FSS environments. Based on the image method, a ray tracing algorithm was implemented in MATLAB.

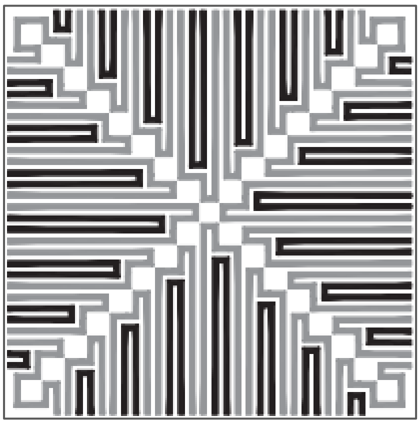


Figure 2.13: Unit cell of interwoven FSS [27]

In contrast, in [27], the authors propose a highly convoluted square loop known as the interwoven FSS to transmit signals at about 400 MHz while reflecting signals above 600 MHz. Figure 2.13 shows the unit cell of the interwoven FSS. By convoluting the FSS element, the unit cell size can be greatly reduced. However, the size reduction needs to be compromised with the bandwidth performance. Thus, in this paper, the adjacent elements are interwoven in order to improve the bandwidth of the FSS.

Table 2.5: Comparison of the previous studies in indoor environments

Authors	**Title**	**Advantages**	**Limitations**
G. H. H. Sung *et al.* [1]	A frequency-selective wall for interference reduction in wireless indoor environments	- examine practical application issues -inexpensive fabrication cost	- time and labor consuming fabrication technique
M. Raspopoulos and S. Stavrou [13]	Frequency selective buildings through frequency selective surfaces	- prediction using ray tracing technique	- high shift in resonance frequency
E. A. Parker *et al.* [27]	Frequency selectively screened office incorporating convoluted FSS window	- reduce unit cell size - bandwidth improvement by interweaving adjacent elements	- high complexity; hard to analyze

Table 2.5 summarizes previous studies of the FSS in indoor environments and their limitations.

2.5.3 FSS for Energy-saving Glass

As previously explained, FSS can be designed not only as the band-stop filter but it also can be designed as the band-pass filter. FSS is commonly used for energy-saving glass to provide good transmission improvement of other useful signals while preserving the infrared (IR) attenuation as much as possible.

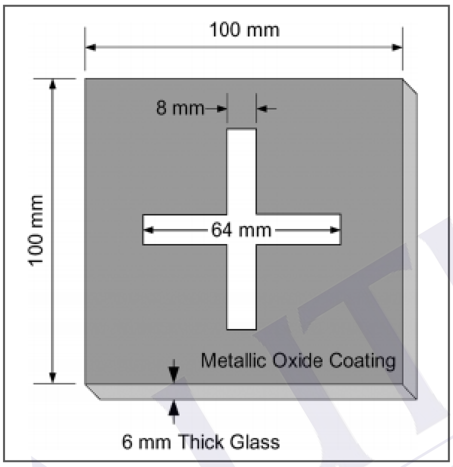


Figure 2.14: Unit cell dimensions of the cross-dipole FSS [14]

For instance, in [14], the authors removed the cross-dipole FSS aperture from the coated glass as demonstrated in Figure 2.14. The cross-dipole FSS element is chosen due to its simplicity, though it is expected that the loop type FSS elements can offer a better performance. Since the glass is more fragile, it is very difficult to etch all other complex FSS elements. It can be seen in this paper that the IR transmission will increase in direct proportion to the removed area. Thus, it is very crucial to remove just a little of the metallic oxide coating when etching the FSS in order to maintain IR attenuation to an acceptable level.