Flexible Multi-Layer Frequency Selective Surfaces for Radio Secure Environments

by

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Abstract

In buildings with multiple occupancy, frequency shielding and re-use methods are required to enhance the spectral efficiency. Passive band stop Frequency Selective Surfaces (FSSs) can be used to improve the electromagnetic architecture of the buildings. This dissertation provides a new approach to the design of spatial filter material (frequency selective surfaces) on a flexible, thin and transparent substrate. The flexibility, transparency and frequency shielding property of these film type structures help them to be deployed on the walls/windows of offices, vehicles, and prisons etc. This technique is a low cost method of confining LAN pico cells in one room. A simple ring FSS of sub wavelength element size ($\lambda_0/4$) can provide transmission stop band at 12.3 GHz. The variation in band stop characteristics was investigated for various wall materials. The centre frequency was varied by more than 3 GHz by common wall materials. A convoluted square loop FSS was developed to miniaturize the FSS element size without changing the unit cell dimensions. The small dimensions of the elements improved the angular stability for incident angles up to $45^\circ$. A frequency reduction of 62% was achieved by modifying the traditional square loop FSS. The bandwidth increased from 2 GHz to 8 GHz using double layer FSS configurations. An offset technique was introduced in the bottom layer in order to maximize the mutual coupling between the two layers of the composite FSS structure. A meandered double layer FSS with the unit cell dimensions much smaller than the operating wavelength ($\lambda_0/22$) shifted the stop band frequency from 8 GHz to 1.89 GHz. The densely packed meandered design showed a stable response for the perpendicular (TE) and parallel (TM) polarizations at oblique incidence. Cascading of these multi-layer FSS showed the band stop remained unchanged but the bandwidth started to increase. For each design, the modelled results are in agreement with the measured results validating the developed prototypes. The factors that govern the performance of FSS such as element geometry, element conductivity, dielectric substrate and the plane wave incident angles were investigated. Screen printed silver on polycarbonate sheet was used for the FSS prototypes. This research has demonstrated single and multi-layer band stop FSSs for shielding windows and walls of offices, vehicles etc. in order to improve the indoor/outdoor wireless
communications. The flexible nature of the substrate, the low manufacturing cost and easy mass production allows, the designed conductive FSS to be rolled into long continuous sheets or wallpapers. This research has drawn a connection between the fields of antenna design, communication systems and the building architecture.
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I could never have the strength of completing my PhD without the unfailing love, support and constructive criticism from my husband Aamer. To him, I dedicate this thesis.
Statement of Originality

This work has not been submitted for a degree or diploma in any university. To the best of my knowledge and belief, this work contains no material previously published or written by another person except where due reference is made in the work itself.

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### List of Acronyms and Symbols

#### Abbreviations and Acronyms

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<tr>
<td>AMC</td>
<td>Artificial magnetic conductor</td>
</tr>
<tr>
<td>CST</td>
<td>Computer aided simulation technology</td>
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<tr>
<td>DS</td>
<td>Double Sided</td>
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<tr>
<td>DS1800</td>
<td>GSM-1800 band</td>
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<tr>
<td>EBG</td>
<td>Electromagnetic bandgap</td>
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<tr>
<td>EC</td>
<td>Equivalent Circuit</td>
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<tr>
<td>EMC</td>
<td>Electromagnetic compatibility</td>
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<tr>
<td>FDTD</td>
<td>Finite-difference-time-domain</td>
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<td>Finite-element-method</td>
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<td>Frequency selective wall</td>
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<tr>
<td>GSM</td>
<td>Global system for mobile communication</td>
</tr>
<tr>
<td>GPS</td>
<td>Global positioning system</td>
</tr>
<tr>
<td>LAN</td>
<td>Local Area Network</td>
</tr>
<tr>
<td>MEK</td>
<td>Methyethylketone</td>
</tr>
<tr>
<td>MIMO</td>
<td>Multiple input multiple output</td>
</tr>
<tr>
<td>MoM</td>
<td>Moment of methods</td>
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<tr>
<td>RCS</td>
<td>Radar cross section</td>
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SS  Single sided
TE  Transverse electric
TM  Transverse magnetic
UMTS Universal mobile telecommunications system
UWB Ultra-wide band
VNA Vector network analyzer
WiMAX Worldwide interoperability for microwave access
WLAN Wireless local area network
WSN Wireless sensor networks
100T 100-Thread Mesh

Symbols

\( f_1 \) - focal point of first feed of dichroic reflector
\( f_2 \) - focal point of second feed of dichroic reflector
\( f_r \) - resonant frequency
\( f_H \) - upper limit frequency
\( f_L \) - lower limit frequency
\( \Gamma \) - reflection coefficient
\( \tau \) - transmission coefficient
\( E_i \) - incident electric wave
\( E_r \) - reflected electric wave
\( E_t \) - transmitted electric wave
\( E_\perp \) - electric field perpendicular to the plane of incidence
\( E_\parallel \) - electric field parallel to the plane of incidence
\( k \) - direction of propagation
\( w \) - element repeat spacing
\( \lambda_o \) - free space wavelength
\( \lambda_r \) - wavelength at the resonant frequency
\( \theta \) - angle of incidence for the plane wave
\( \varepsilon_r \) - relative permittivity
\( \varepsilon_{\text{eff}} \) - effective relative permittivity
\( S_{11} \) - the reflection coefficient
\( S_{21} \) - the transmission coefficient
\( d_{\text{farfield}} \) - far field distance between antenna and the FSS
\( D \) - longest linear dimension of the radiating aperture
\( \beta_{xz} \) - half power beam width in \( xz \) plane
\( \beta_{yz} \) - half power beam width in \( yz \) plane
\( l_x \) - the width of horn antenna
\( l_y \) - the height of horn antenna
\( L \) - Inductance
\( C \) - Capacitance
\( M_l \) - mutual inductance
\( M_c \) - mutual capacitance
\( \eta \) - Efficiency
\( \sigma \) - Conductivity
\( \delta_x \) - half-cell displacement in \( x \) direction
\( \delta_y \) - half-cell displacement in \( y \) direction
\( Z_o \) - free space impedance
\( Z_l \) - characteristic impedance
\( n \) - number of meanders
CHAPTER 1

INTRODUCTION

1.1 OVERVIEW

For the past few years, frequency selective surfaces (FSSs) have received significant attention due to their ability to control the propagation of electromagnetic waves. The FSS originated from the mesh and strip grating concepts that were exploited in the optical regime. Extensive research has been conducted to translate and apply these concepts in the microwave and millimeter wave regions, predominantly for antenna systems in fixed as well as mobile services [1]. Because of their filtering capability of electromagnetic waves, they have been used in many applications ranging over much of electromagnetic spectrum such as antenna radomes, multi-band antennas, spatial filters, microwave absorbers, dichroic reflectors, artificial electromagnetic bandgap materials, electromagnetic filtering and wireless security devices in indoor outdoor communication. A simple household application of these notch band FSS is the microwave oven door made of glass covered metal grids. The perforated holes in the grid blocks the microwave radiation from leakage, ensuring the user safety, while allowing the visible light to pass so that the user can observe the food cooking inside the oven. For indoor outdoor wireless communication privacy, an attempt to isolate the signals or cancel the interference between the co-existing systems is made by transforming the building walls/windows into frequency selective surface walls/windows. These walls can filter out the undesired frequency while allowing other
desired frequencies to pass through. The potential use of wall paper type FSSs can be in vehicles which block interference, in prisons to shield radio signals except the handheld transceiver frequency band, and in office buildings for isolation or reuse of desired frequency bands by multiple users. These applications are briefly discussed in the Section 1.4 of this chapter.

A classical FSS is a periodic surface comprised of identical metal elements arranged in two dimensions forming an infinite array. These elements are either printed on a dielectric substrate or etched through a conductive layer, forming capacitive or inductive structures. When exposed to electromagnetic radiation, the FSS generates a scattered wave with a specific frequency response. As a result some frequencies pass through, and some are blocked by the FSS screen. These structures have also enhanced the communication capabilities of reflector antenna systems for telecommunication satellite platforms [2] by allowing multi frequency illumination of the main reflector.

1.2 STATEMENT OF PROBLEM

With the rapid development in telecommunications where wireless signals have taken over traditional physical cabling, concerns regarding the security and privacy of these free air signals are increasingly important. Demand for the frequency reuse within buildings, offices, vehicles etc. is also an issue. Due to the proliferation of wireless devices in our work place, radio signals can propagate beyond their intended receivers and cause interference with neighboring devices/users. Suitable electromagnetic screening in commercial buildings with multiple occupancy, or in vehicles like aircraft, trains, buses etc., can assist in blockage or passage of certain frequency bands or efficient frequency reuse, as shown in Fig 1.1. The electromagnetic architecture of a building can be enhanced
by using a passive stop band FSS which can improve the spectral efficiency whilst retaining the optical transparency of windows. The application of a traditional FSS at cellular band is limited by the design complexity, angular sensitivity, large size and high cost of fabrication.

Figure 1.1 Potential shielding applications of frequency selective surfaces. (a) FSS windows can be incorporated in trains to prevent unwanted radiations to enter or exit. (b) In office environments, windows and walls can be shielded in order to prevent mutual interference between multiple offices. Other examples like personal hand phone systems in offices may need shielding so that radio waves are prevented from leaking into or out of the office rooms.
1.3 MOTIVATION OF RESEARCH

Depending on the type of application, there are certain instances where radio signals need to be confined to an area of interest, thereby lowering the interference and improving the wireless security. This has led to the motivation of this research; to design and develop frequency selective surfaces with improved functionality and performance for shielding applications. The first step in this research was to examine the basic underlying theories of FSS and an in depth description of their analysis. The electrical properties as well as the specific physical characteristics that have been focused on in this research are the flexibility, thinness and optical transparency of the designed FSS. A novel approach of designing FSS on thin flexible transparent layer of dielectric material is introduced which is intended to find application in antenna radomes or windows of aircrafts and other vehicles whilst retaining the optical and desired radio frequency transparency.

The analysis offers useful physical insight of the structure, which is formulated through an equivalent circuit model representing the FSS. Various design configurations like single sided and double sided FSS were also considered which resulted in lowering of resonant frequency, increase in bandwidth and suppression of harmonics of the intended frequency response over the range of angle of incidence. The transmission response of the designed FSS over target materials like glass, wood, concrete etc. for wall/window configurations is reported. The FSS performance at different incident angles is an important design criterion to consider. Moreover, the unit cell area was reduced without compromising the miniaturized nature of unit cell. For all the designed FSSs discussed in this thesis, the element sizes are smaller than $\lambda_o/8$ in dimension where $\lambda_o$ is the operating wavelength in free space..
The comprehensive study and analysis of each FSS was done in the following sequence:

1) Study the effect of primary design factors like supporting dielectrics, unit cell size, metal track widths, inter-element spacing and the periodicity on the transmission/reflection plane wave performance.

2) Design an FSS with minimum sensitivity to angles of illumination and polarization of the incident plane wave. The lattice geometry and element type are chosen in view of angular stability.

3) Optimization of the FSS at the desired frequency for specific applications.

4) Prototype manufacture and testing.

1.4 COMMON APPLICATIONS OF FSSs

Due to the plethora of FSS element types and their unique features, FSSs have been employed in a variety of applications, often with firm specifications. The shape and arrangement of those elements in a proper grid play an important design role. A simple and perfect example of an FSS is the perforated metal screen door of a standard household microwave oven which blocks the microwaves while allowing the light waves to pass (see Fig. 1.2). The microwaves at 2.4 GHz inside the oven are blocked, acting as a closed metal shield, while allowing the visible light to escape and thus behave as a high pass filter.
Figure 1.2 Microwave oven with FSS slots embedded on the front door.

The flat or curved FSS have offered high channel capacity whilst maintaining the high performance standards of various microwave antenna systems. An application of this FSS is using as a dichroic sub reflector. The FSS is placed in between a feed and the main reflector as shown in Fig. 1.3. The FSS is transparent at frequencies $f_1$ (focal point of first feed) and reflective at other frequency band $f_2$ (image point of second feed). The main reflector can therefore, accommodate both the frequency bands ($f_1$ & $f_2$), saving on space and cost [1, 2].

Figure 1.3 Frequency selective surfaces as dichroic reflector, transparent at $f_1$ and opaque at $f_2$. 
A famous application of an FSS is band pass radomes used to reduce the radar cross section (RCS) of antennas outside their operating band. RCS is defined as the product of geometric cross section, fraction of power scattered (reflectivity) and the direction in which the power is scattered (directivity) by the target. In Fig. 1.4, a shaped radome covering the radar antenna is placed on the front of an airplane. When the radome is opaque, most of the incident signals are reflected in a bi-static direction producing weak signal in the back scatter direction thereby reducing the radar cross section of the antenna. This kind of application is widely deployed in military services which use stealth technology in their aircrafts and ships with low detectability [1].

Figure 1.4 Use of hybrid radome made up of band pass frequency selective surface to reduce the antenna radar cross section out of band.

FSS structures have been used in designing artificial magnetic conductors (AMC) and electromagnetic bandgap materials (EBG). The most well-known example of AMC structures is the high impedance surfaces designed by Sievenpiper [3]. This high impedance surface is used as a ground plane which blocks the propagation of surface waves within the
substrate and thus can be employed in designing of antennas to improve the performance [4].

FSS are also used in frequency selective shielding in EMC applications. Shielding enclosures are mainly used to prevent the effect of external electromagnetic fields and the leakage effects from the interior radiative components. For example, bandpass shielding enclosures are used for the portable digital wireless devices [5]. Other than equipment shielding, frequency selective surfaces are also finding their way into walls and windows of buildings in order to improve their wireless security, i.e. blocking undesirable frequency bands and passing the useful ones. Screen printed FSS arrays have been examined by placing them on various target objects i.e. wall materials like concrete, wood or glass in order to find the effect on transmission characteristics with and without the FSS [6]. This allows adjacent rooms to be isolated for one LAN for frequency reuse, while the other frequencies pass through the wall with minimum attenuation. FSSs have also been used to improve the wireless communication by creating efficient radio frequency management in buildings with energy saving windows [7]. The finite size frequency selective structures comprising of $3 \times 3$ elements separated by low density polystyrene foam were developed particularly for longer wavelengths. This structure demonstrated that a passband can be inserted in a reflective or absorbing wall, thereby improving the efficiency of use of radio spectrum in buildings [8].

With the use of energy saving glass or low emissivity (low-e) glass windows in modern buildings that can transmit visible light and reflect infrared, the attenuation of RF/Microwave signals associated with mobile phones, Wi-Fi, security and personal communication systems is of interest. This energy saving property is achieved by applying
a thin metallic coating on either side of ordinary float glass panes. These windows are commercially available at large scale and are widely used in buildings and vehicles [9].

However, to overcome the drawback of blocking the electromagnetic radiation through thermal glass windows a solution whereby frequency selective surfaces are embedded in the window was created. The FSS behaves as a bandpass filter and the bandwidth covers the important frequencies for GSM, GPS and UMTS without degrading the thermal insulation of glass windows. Gustafson used a similar principle where hexagonal slits were engraved much deeper than the metallic coating into glass window and provided the desirable transparency in the frequency range from 900 MHz – 2 GHz [10]. Measurements showed a frequency selective window has approximately 10dB better transmission in the 900 MHz – 2 GHz than the original window. However, manufacturing of these hexagonal slits suffered several deviations from the original design due to the deep engraving than the actual thickness of the metallic coatings. A more severe restriction in the measurements was the size of window which was 400 x 400 mm² and not an actual standard window size. Also there was no direct comparison made between theoretical and measured results. A bandpass aperture type cross dipole FSS etched in the metallic coatings of low-emissivity glass to improve the transmission of electromagnetic signals while blocking the infrared radiations was reported in [11]. One drawback was the removal of the coating when the FSS was etched which increases the IR transmission. A double bandpass FSS [9] was also designed in order to improve the transmission of UMTS and Wi-Fi signals through the energy saving glass with stable frequency response. No fabricated prototype and experimental results were presented.

The challenge is finding an appropriate flexible substrate and the choice of conductive material to design FSS which has fewer losses. A recent interest is in designing
the FSS with unit cell dimensions much smaller than a wavelength so that the overall electrical size of the surface is small. These surfaces are required to show low sensitivity with respect to the angle of incidence of incident plane waves. These issues have been addressed and put to test in this research.

1.5 ORGANISATION OF THESIS

An overview of each chapter is as follows:

Chapter 1:

This chapter presents the statement of the problem, motivation and objectives of this research. An overview of all the chapters is also given. While the underlying theoretical description of the FSSs is well established, much work is still needed to produce workable FSS designs. A few common applications are discussed. There are some shielding applications where simple element geometries can be useful, but applications involving curved surfaces, space constraints, flexibility of overall structures or broad bandwidth coverage require significantly more complex configurations to be developed.

Chapter 2

This chapter provides the background including evolution, development history and the ongoing research of the FSS and theory required for comprehensive study of FSSs. The typical behavior of commonly used FSS elements and the significance of the backing substrate are presented. The theoretical qualitative analyses for certain lattice and element geometries of FSS structures are examined. Objectives of this chapter include highlighting the guidelines for designing of FSS, strategies to avoid grating lobes, and the variation of the minimum resonant frequency with the angle of incidence and polarization. The main aim of this chapter is to identify the key factors which govern the FSS performance,
different configurations of FSS-dielectric layers, reviewing the available techniques for analysis of FSS and how the limitations are overcome by our FSS designs.

Chapter 3:

This chapter describes about the modeling procedure, the fabrication technique used and the measurement configuration for all the designed structures, including the hardware equipment. FSSs were modelled and investigated using CST Microwave studio, a full 3D wave simulation tool. Thin transparent, flexible FSS prototypes were then manufactured using screen printing technique. Finally, the measurement set-up used for calibrating the prototypes and measuring the scattering parameters at normal and off-normal incidence is described.

Chapter 4:

This chapter deals with the analysis and transmission/reflection plane wave performance of a single layer planar FSS formed by a ring array of unit cells. For the sake of analysis, the unit cells are assumed to be infinitely thin and highly conducting (silver metal rings). Due to the large number of FSS element geometries and variations, it is difficult to describe each in detail. Instead, the prototype of representative ring array was manufactured using screen printing technology. The chapter includes the results, parametric study and the circuit model development. Moreover, inclusion of the packing dielectric substrate and its effect on transmission bandwidth are investigated.

The analysis of a simple ring provided the fundamental tools, which were further applied to analyze the convoluted structures on a single layer of substrate discussed in the latter half of this chapter. As physically smaller unit cells are advantageous at long wavelengths, so there are significant advantages in retaining the unit cell size, but with a reduced resonant frequency. It is shown how convoluting a basic loop type FSS can:
a. improve the stability of the resonant frequency over angles of incidence,
b. increase the separation between the resonant and the grating frequency,
c. have a and screen printable drawing,
d. help in miniaturization of the FSS element while retaining the actual unit cell size.

Modified FSS design specifications; parametric study and circuit model development are also included. The prototype was manufactured and tested, simulated and measured results are compared to simulation. The performance of the FSS on glass windows is reported.

**Chapter 5:**

Based on the basic square loop FSS and the equivalent circuit developed in Chapter 4, a double layer configuration with similar metallic pattern on the reverse side of the substrate is presented. The filtering response of a single layer series resonant FSS (Chapter 4) suffers from narrow bandwidth for higher inductance and low capacitance designs. Therefore, two FSS structures printed on each side of a dielectric were examined to see how the bandwidth and the filtering response can be increased. Furthermore, various offset techniques were introduced to achieve maximum coupling between the two surfaces. The effects of lateral displacement between the top and bottom layers affects the mutual inductance and capacitance between the conducting elements are discussed. The frequency response of the FSS at different displacements are compared. The behavior of this FSS at normal and off-normal angles of incidence is also presented. The basic design specifications and a parametric study to further enhance the bandwidth are reported. This chapter establishes the fundamentals of the reconfigurable symmetrical multilayer design with zero or half-cell displacements.
The use of FSS at cellular mobile bands like GSM is new because of their requirement for large unit cell size (>10 mm) for them to resonate at lower frequencies. In the latter part of this chapter, square array elements are miniaturized using a meandered structure and a double-layer configuration. At cellular band (1.89 GHz), large array elements with dimension ($\lambda_c/22$) were miniaturized using a meandered structure and double layer FSS configuration. Based on the knowledge gained from the results of in previous chapters, it is possible to design an FSS which can be used for shielding cellular frequencies. Maximum coupling was achieved by convoluting the basic loop type FSS element and offsetting the layers. The design specification, convolution stages, and lumped element model are presented in this chapter. The design is validated by good agreement between the measured and simulated results. Screen printing technology proved to deliver high precision accuracy in spite of the miniaturized nature and packing of resonant lengths in this structure.

Chapter 6:

This chapter includes the applications of FSS. The single-layer planar ring type FSS can provide room isolation for a LAN for frequency reuse, while other frequencies pass through the walls with minimal attenuation. Next, potential application for the double-layer convoluted type for GSM frequency shielding in radomes and other microwave systems is illustrated. The screen printed FSSs are thin, transparent, flexible, conformal, and easily mass produced thus making them suitable for large walls and windows frequency shielding.

Chapter 7:

This chapter summarizes the important results of this dissertation. These include a comparison between simple and complex FSS design and their absorbing properties, tunability, configurability and spectral response. Optimization and fabrication techniques
are also discussed. This is followed by a discussion on the potential of future developments of FSSs.

1.6 ORIGINAL CONTRIBUTION

The main contribution of this thesis is to provide a flexible conformal and transparent frequency selective surface which behaves as a stop band filter at specific bands while passing other useful signals. The screen printing technique is used to print the metallic patterns on the transparent thin substrate which can be readily applied on any existing surface. The research was extended from single layer FSS to double layer configurations using layer offset techniques. The parametric analysis showed how the element geometry can vary the notch frequency, bandwidth and can be tailored as per the desired RF applications. The problem of designing large unit cell in order to block lower frequencies was addressed by convoluting the FSS element maintaining the FSS unit cell size. This led to decrease in the electrical size of the overall surface thereby miniaturisation the structure. The concept was further applied to the shielding effect on the radio wave propagation through the window panes in office buildings in order to provide radio secure environments. This research can be considered as an important step in realizing a practical commercial product - FSS windows.
1.7 PUBLISHED WORK

1.7.1 Journal Papers


1.7.2 Conference Papers


1.8 REFERENCES


CHAPTER 2

FREQUENCY SELECTIVE SURFACES: THEORY

2.1 INTRODUCTION

In the current era of telecommunications involving wireless systems, the security, protection and isolation of signals from each other is of utmost importance. In this context, frequency selective surfaces (FSSs) represent an attractive technology. In the late eighteenth century, the American physicist Rittenhouse discovered the first clue about the existence of selective transmission through materials at different frequencies. While observing a street lamp through a silk handkerchief, he discovered that some colors of the light’s spectrum where passed while others were suppressed [1]. In 1919, Marconi patented these periodic metallic grids for filtering radio frequency waves with different polarizations [2]. The transmission through a periodic array of conducting strips was exploited in the optical regime highlighting the features of these structures [3].

In 1946, these surfaces were known as frequency selective surfaces and the basic properties of simple FSS structures emerged in published reports [4, 5]. FSS structures were modelled using multiple dielectric spacers/layers with FSS structures etched on or embedded within dielectrics. The theory of phased array antennas provided the starting point for the study of FSS [6]. During the late 60’s methods were adopted to achieve accuracy in the modelling of FSS electromagnetic properties [7, 8]. More sophisticated
FSSs like planar, curved and multiband FSSs were designed with the emergence of computational electromagnetic codes in the 1990’s [9, 10].

By definition, a frequency selective surface (FSS) is a periodic assembly of identical elements arranged in a one or two-dimensional infinite array. The array can be free standing or backed by a supporting dielectric layer. Some of these periodic elements have a broadband spectral response whereas others have a narrow-band response. The choice of the proper element in the design of an FSS is thus very significant for a target application [11]. Munk [11] authored a comprehensive account of the history and design techniques of the classical FSS. Under illumination of an electromagnetic wave, a FSS acts like a frequency-domain filter: some frequency bands are transmitted and others are reflected or absorbed.

Unlike a classical microwave filter [11], the spatial filter or frequency selective surface is much more complex. In all filters, the frequency is varied at the input port and the response is recorded at the output. In a spatial filter, the incident field arrives at various angles of incidence as well as different polarizations. This has a profound effect on the transmission properties of the structure. Various techniques are used in analyzing the effects of wave propagation on the frequency selective surfaces i.e. the transmission of the wave through the FSS and the reflection of RF energy from the FSS plane. These are expressed in terms of the scattering parameters commonly associated with most RF devices. The techniques are briefly reviewed in this chapter.

Frequency selective surfaces have been widely used for filtering and shielding applications and have enhanced the communication capabilities of some antennas [12]. The feature of shielding the communication facilities led to the potential application of
frequency selective surface radomes for radar cross section (RCS) reduction of antennas, outside their frequency band of operations. This radome application is widely used by the military for missiles, aircraft and ships. The antenna is covered with an FSS that is transparent at the operating frequency, but opaque at other frequencies. The FSS layers are integrated in a way that they retain the antenna performance, the filtering performance for anti-interference and reduced RCS.

In this chapter, we present the commonly used element types, their specifications, the elementary principle and typical electromagnetic behavior. The effects of element lattice spacing are explained to illustrate how FSS designs can reduce the grating lobe problem. Various factors that govern the FSS response like element geometry, conductivity of the elements, dielectric substrate profile, incident angles and the polarization of the plane wave illuminating the surface are also discussed. The shapes and configurations chosen for the FSS elements are limited by the imagination of the designer. This chapter reports some of the research done on the major aspects and the underlying theories. A simple dipole (slot/patch) element acts as a spatial filter, but variations in this basic structure leads to much more complex FSS arrangements. A list of electromagnetic parameters of significance are given in Table 2.1
Table 2.1 Important properties of FSS structure

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Notes</th>
</tr>
</thead>
</table>
| Resonant Frequency, $f_r$ | • $|S_{21}| < 10$ dB  
• Stopband/passband resonant frequency, $f_r$ should remain constant for different angles of incidence and polarization.                                                                                  |
| Bandwidth           | • $|S_{21}| < 10$ dB (measured in %)  
• Narrow and wide bandwidth depends on the inter element spacing which must be less than $0.4\lambda_r$.  
• Cascading of FSS screens at $\lambda_r/4$ distance from each other also enhances the bandwidth.                                                                 |
| Unit cell Size       | • Geometry of the structure in one period.  
• For resonance to occur the element length should be multiple of half the resonant wavelength, $\lambda_r$.                                                                                                 |
| Dielectric Profile   | • High permittivity of substrate improves the FSS angular stability but leads to high transmission loss if the dielectric substrate has high loss tangent.  
• One layer dielectric slab with thickness less than $0.05\lambda_r$, FSS printed on one side, the resonant frequency shifts downward by $f_r/\sqrt{((\varepsilon_r + 1)/2)}$  
• Two layer dielectric slab with each of thickness less than $0.05\lambda_r$ and embedded FSS, the resonant frequency will change between $f_r$ and $f_r/\sqrt{\varepsilon_r}$. |
| Attenuation at resonance | • Should be more than $20$ dB.                                                                                                    |
| FSS material         | • Highly conductive material is used to fabricate FSS structure.  
• The depth in the attenuation curve depends on the conductivity of the FSS elements.                                                                                                      |
2.2 BASIC PRINCIPLE OF PLANE WAVE TRANSMISSION

When an incident plane wave encounters an impedance difference at the boundary, the wave is partially reflected back to the source and partially transmitted through the medium [13]. The wave reflection and transmission through the planar boundaries can be explained in two parts: (a) normal Incidence ($\theta = 0^\circ$) and (b) oblique incidence ($\theta \neq 0^\circ$) as shown in Fig. 2.1.

![Ray representation of the plane wave incidence on a FSS array (a) normal incidence (b) oblique incidence.](image)

**Figure 2.1** Ray representation of the plane wave incidence on a FSS array (a) normal incidence (b) oblique incidence. The black dashes represent the metallization on top of the dielectric medium 2.

2.2.1 **Plane wave at normal incidence**

A periodic surface FSS is a thin layer of conducting elements often printed or etched on a dielectric substrate for mechanical support [3]. A periodic surface behaves as a passive array when excited by an incident plane wave. This research is based on a passive array because of their planar, simple and more accurate response in terms of angular sensitivity. An active array behaves as a periodic surface when the elements are driven with an equal amplitude and linear phase variation. Fig 2.2 shows a passive array of conducting dipoles in a square lattice arrangement. The dipole element is considered because of its
simple design and its ease of demonstrating FSS behavior. The incident plane wave \( E_i \) is partially reflected back in specular direction \( E_r \) and partially transmitted in the forward direction \( E_t \). The reflection coefficient \( \Gamma \) of the FSS structures is commonly defined as [11]:

\[
\Gamma = \frac{E_r}{E_i}
\]  

(2.1)

and the transmission coefficient \( \tau \) of the FSS structure is formulated as:

\[
\tau = \frac{E_t}{E_i}
\]  

(2.2)

Figure 2.2 (a) Periodic array of passive dipole conductors. The FSS structure is illuminated by an incident \( E_i \) electromagnetic wave, which is partly, reflected \( E_r \) and partly transmitted \( E_t \). (b) The reflection coefficient \( \Gamma \) (c) The transmission coefficient \( \tau \).

Also at normal incidence, the relation between the reflection and transmission coefficient is given by [13]:

\[
\tau = 1 + \Gamma
\]  

(2.3)
2.2.2 Plane wave at off normal incidence

The electric and magnetic fields of a normally incident plane wave ($\theta_i=0^\circ$) are also tangential to the boundary regardless of the wave polarization. They are thus independent of wave polarization of the incident wave. It is not the case when $\theta_i \neq 0^\circ$ i.e. for oblique angles of incidence, as shown in Fig. 2.3. A polarized wave can be described as the superposition of two orthogonal waves:

(a) One with electric field perpendicular ($E_\perp$) to the plane of incidence called transverse electric (TE) polarization.

(b) Other with electric field parallel ($E_\parallel$) to the plane of incidence called transverse magnetic field (TM) polarization. It is called so because the magnetic field is perpendicular to the plane of incidence.

![Figure 2.3](image)

**Figure 2.3** Two polarization configurations (a) perpendicular polarization when $E$ is perpendicular to the plane of incidence. (b) parallel polarization when $E$ lies in the plane of incidence. The plane of incidence is defined as the plane containing the surface normal to the boundary and the direction of propagation, $k$ [13].
An arbitrary polarization must be analyzed separately for TE and TM cases. The fields are expanded as a set of Floquet modes for a flat and infinite FSS structure. The TE and TM modes have a direct relation with the angle with which the plane wave is incident on the FSS [14]. These variations need to be minimized or diminished in order to design an ideal FSS. This can be controlled by the proper choice of element shape, and dimensions, and by introducing dielectric substrates or multilayer FSS [15-17].

2.3 SLOT AND PATCH COMPLEMENTARY STRUCTURES: Babinet’s Principle

As discussed in section 2.2.1 a periodic surface is an assembly of identical elements arranged in a one or two-dimensional infinite array [11]. Often an FSS is characterized by its band pass or band stop feature. A single FSS with a band stop is generally of patch form, whereas a band pass is of the slot form, as shown in Fig 2.4. In the low frequency limit, the slot FSS is indistinguishable from a uniform perfect conductor whereas the surface made of patch element is transparent [18]. The incident EM wave excites electric currents on the patch elements, whereas in slots the voltage distribution occurs across the edges of the slot leading to circulating currents [11]. When symmetrical, the same shape slot and patch are superimposed, a perfect conducting plane is obtained and the arrangement is called as Babinet’s complementary array. Babinet’s principle states when the field behind a screen with an opening is added to the field of a complementary structure, the sum is equal to the field where there is no screen [19].
Figure 2.4 Babinet complementary array of (a) dipole/patch and (b) slot elements. Dark regions represent metal.

In [19], a slot-patch complementary array based on Babinet’s principle was designed in order to have stable pass band for normal and oblique incidences with less than 2% frequency shift. However, the inter layer dielectric thickness is critical as far as violation of Babinet’s principle is concerned. With an increase in dielectric thickness or an increase in separation between elements (slot or patch), differences start to appear in transmission response and the bandwidth [11]. When designing a complementary array, the modelling of slot and patch arrays with high accuracy is therefore important.

2.4 FSS FILTER TYPES

From Babinet’s principle, the reflection properties of one array correspond to the transmission of the complementing array [20]. Regarded as the spatial filters of electromagnetic waves, an FSS is typically a flat composite metallic surface designed to be transparent in some frequency bands, and reflective, absorbing or redirecting in others. These filters (or dichroic filters as they are alternatively known) can be categorized into four major categories: low pass, high pass, band pass and band stop filters (see Fig. 2.5).
Babinet’s principle can be employed to transform a band stop FSS to a band pass FSS, and a high pass to a low pass FSS. The stop band FSS is most commonly used. Depending on the design requirements, the bandwidth, sensitivity to electromagnetic wave incidence angle and level of attenuation can be controlled.

### 2.5 FACTORS THAT GOVERN THE FSS RESPONSE

The performance of the FSS is governed by the element shape, element dimensions, element conductivity, the supporting dielectric and the incident angle illumination. In many applications it is important for the FSS to provide consistent response over varying angles. Dielectric permittivity and the element conductivity can affect the spectral response of the FSS. Apart from the element geometry, which plays the fundamental role in design of an FSS, the arrangement of elements in a lattice grid is equally important. For numerical analysis, these arrays are assumed to be infinite in dimension. The finite array approximation reduces the complex analysis problem by calculating the frequency response of a single element in the array and applying the periodic nature of the FSS.
2.5.1 Lattice Geometry and grating lobe phenomenon

On a frequency selective surface, the elements are periodically arranged. The lattice geometry can be square, brick spacing or triangular depending on how densely packed a surface is required. However, elements without a proper lattice grid can lead to ‘grating lobes’ used to describe the undesirable scattering of energy in the form of secondary beams occurring at angles with higher order constructive interference [21]. The occurrence of grating lobes has a direct relationship with the element spacing and the angle of incidence of the plane wave illuminating the structure. Consider two simple dipole arrays with different element repeat periods with respect to operating wavelength as shown in Fig 2.6 (a) and (b). Once the element repeat period becomes electrically large, the out of phase signals are excited between the adjacent elements, which produce nulls and secondary beams other than the main propagation beam (see Fig 2.6(b)).

![Figure 2.6](image)

**Figure 2.6** Grating lobes are generated from a dipole array (a) For repeating period < \( \lambda \), the main beam radiation has no grating lobes (b) For repeating period >\( \lambda \), the main beam radiation has multiple grating lobes [14].

In order to avoid the scattering of energy in undesirable directions, the repeating element period should be less than the shortest wavelength for the broadside incident angle.
For larger incident angles, the repeating element period should be half the free space wavelength in order to avoid the grating lobes \cite{22}. This is considered as a general rule of thumb while designing an FSS.

The equation used for suppressing the grating lobes is given by \cite{21}:

\[
\frac{w}{\lambda} < (1 + \sin \theta) \tag{2.4}
\]

Where \( w \) is the element repeat spacing, \( \lambda \) is the operating wavelength and \( \theta \) is the angle of incidence for the plane wave. A reflection coefficient of unity is achieved when the reflected wave is grazing the array \cite{11}. Further, if the criteria is violated conducting elements can no longer be modelled as pure reactive components, a resistive component will emerge which corresponds to the energy loss due to grating lobes. It should be noted from equation 2.4 that the grating lobe occurrence depends on the spacing between repeating elements and the angle of incidence. However, the dielectric substrate does not affect the frequency where grating lobes start to become apparent \cite{21}.

In \cite{9}, several element spacing lattices were investigated with a view to overcome the grating lobe problem. In Table 2.2, the maximum spacing criteria is given in order to avoid the peak or shoulder region of a grating lobe from entering the free space. The given spacing requirements serve as the vital design rules that cannot be ignored.
Table 2.2. The grating lobe criteria and different FSS lattice geometries [9].

<table>
<thead>
<tr>
<th>Lattice Type</th>
<th>Max. Allowable Spacing</th>
<th>$\theta = 0^\circ$</th>
<th>$\theta = 45^\circ$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Square Lattice</td>
<td>$\frac{w}{\lambda_o} &lt; \frac{1}{(1 + \sin \theta)}$</td>
<td>$\frac{w}{\lambda_o} &lt; 1$</td>
<td>$\frac{w}{\lambda_o} &lt; 0.59$</td>
</tr>
<tr>
<td>$60^\circ$</td>
<td>$\frac{w}{\lambda_o} &lt; \frac{1.15}{(1 + \sin \theta)}$</td>
<td>$\frac{w}{\lambda_o} &lt; 1.15$</td>
<td>$\frac{w}{\lambda_o} &lt; 0.67$</td>
</tr>
<tr>
<td>$63^\circ$</td>
<td>$\frac{w}{\lambda_o} &lt; \frac{1.12}{(1 + \sin \theta)}$</td>
<td>$\frac{w}{\lambda_o} &lt; 1.12$</td>
<td>$\frac{w}{\lambda_o} &lt; 0.65$</td>
</tr>
</tbody>
</table>

$\lambda_o$ is the resonant wavelength of the FSS.

2.5.2 Element Types

The shape of the conducting or resonating elements in an FSS is unrestricted. According to Munk [11], the elements can be arranged in four possible configurations.

(a) Center connected

This group includes straight dipoles, tri poles, loaded tri poles and anchor elements, Jerusalem cross and square spiral elements (see Fig 2.7).

Figure 2.7 Various center connected types of FSS.
The dipoles provide a simple design whereas the tripoles can be packed tightly in a triangular lattice forming a super dense surface and a larger bandwidth. By loading the tripoles i.e. by adding element end capacitance, the bandwidth can be further increased. However it can limit the dense packing of elements. The end loading of cross element gives rise to the Jerusalem cross and is one of the oldest elements being investigated. The square spiral element is basically a cross element which has flexibility to add more turns to the spiral pattern which can increase the end capacitance (see Fig 2.7). Thereby provides a broader bandwidth. A detailed study of the centre connected element type has been undertaken in [11, 15, 23, 24].

(b) Loop Type

This group includes square loop, pentagons, hexagons, four and three legged loaded elements as shown in Fig 2.8.

![Loop type elements](image)

Figure 2.8 Loop type elements

The circumference of the centre connected element type is widened forming the loop type elements. The four-and three-legged elements resonate when their circumference is one full wavelength. However, the three-legged element is considered to be more broad banded than the four-legged loaded element, the reason being the inter element spacing is smaller in the former than the latter. Similarly, out of basic loop types, hexagon provides the superior bandwidth when placed closely, minimizing the inter element space. A detailed study of loop type elements has been done in [11, 25-27].
(c) **Solid Interior type**

This includes plate elements of simple shapes like circular disks, squares, pentagons and squares as shown in Fig 2.9. These elements have solid interior and were among the first to be investigated [28].

![Solid Interior or Plate Type Elements](image)

Figure 2.9 Solid interior or plate type elements.

The drawback of using these types of FSS elements is that the element dimension which is close to half of the operating wavelength ($\lambda/2$), which further demands inter-element spacing to be large, leading to early onset of grating lobes and angular instability. A detailed study and the major contribution was made by Lee [29, 30] and Chen [31].

(d) **Combinations**

This group includes the sophisticated patterns with combinations of the elements from groups mentioned above. Endless combinations and variations are possible depending upon the desired application. A few of these elements are shown in Fig 2.10.

![Various Combinations](image)

Figure 2.10 Various combinations can be made using loop, centered and plate type elements.
These types of elements are basically used to overcome any filtering or design deficiencies that are associated with the simple elements. However, care is needed when printing these elements, as high printing accuracy is required [32, 33]. In this research, the focus is on examining the frequency shielding performance of single-layered single-sided or double-sided FSS with simple or sophisticated FSS elements. Each shape possesses its own unique frequency characteristics, such as the level of band separation, operating bandwidth, level of cross polarization and dependence on the angle of incidence. Table 2.3 summarizes the performance of a few commonly used FSS elements (numbers signify the score based on performance).

**Table 2.3. Performance of several single layer freestanding FSS elements [21].**

<table>
<thead>
<tr>
<th>Element type</th>
<th>Angular Stability</th>
<th>Cross-polarization Level</th>
<th>Larger Bandwidth</th>
<th>Small band separation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dipole</td>
<td>4</td>
<td>1</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>Crossed dipole</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Jerusalem Cross</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Tri pole</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Square Loop</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Ring</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

Score rankings (best =1, second best =2,...). The table shows that the dipole array is very sensitive to the angle of incidence.

**2.5.3 Element Conductivity**

The choice of conducting material is very important and influenced by two factors: (a) the conductivity of the material, which significantly effects the FSS element and (b) the width of the conducting material, which affects both the resistance of the FSS and the optical transparency. The overall performance of the FSS deteriorates as the metallic
elements become lossy and power is dissipated in the element. From the report in [34] the use of highly conductive material leads to high attenuation in the notch band. Thus, a resistor is introduced in the equivalent circuit model to help lessen the attenuation at the resonance.

In this research, silver ink paste (95% silver) was used to fabricate the FSS elements backed by a thin flexible dielectric substrate. The silver ink has superior performance with a relatively low cost of production. Compared with copper, the silver ink has much lower conductivity resulting in a higher resistive component. Since, the silver ink is opaque, the widths of the conductive elements must be small in order to retain the optical transparency of the frequency selective surface screen. Studies show that transparent conductors can be used as conductive elements of FSSs provided the surface resistance is less than 4-8 Ω/square [34]. The silver ink paste used in this research provides a sheet resistance of <0.025 Ω/square/mil [35].

2.5.4 Dielectric Substrate

A dielectric substrate is required for mechanical strength. The dielectric material has a profound effect on the properties of frequency selective surfaces [15]. The frequency selective surfaces can be either embedded within dielectric slabs as in Fig 2.11 (a), or printed on one side of dielectric slab as in Fig 2.11(b). If the FSS is embedded in an infinite dielectric substrate with relative permittivity, \( \varepsilon_r \), the resonant frequency \( f_r \) would be reduced by factor \( \sqrt{\varepsilon_r} \). For a finite thickness of dielectric substrate, the resonant frequency will vary between \( f_r \) and \( \frac{f_r}{\sqrt{\varepsilon_r}} \). For slab thicknesses as small as 0.05\( \lambda_e \) where \( \lambda_e \) signifies the wavelength in the dielectric, the resonant frequency stays close to \( \frac{f_r}{\sqrt{\varepsilon_r}} \). When an FSS is
printed on one side of the dielectric slab, the largest frequency shift downwards would be approximately \( \frac{f_r}{\sqrt{(\varepsilon_r+1)/2}} \) [11].

For thin substrates, the higher order evanescent modes excited by the conducting elements are significant which modifies the energy stored by the FSS elements and alters the resonant frequency [15]. Both embedded and surface bound configurations improve the angular stability in addition to the mechanical stability of the FSS. This explanation is supported by Snell’s law of refraction which shows the effective angle of incidence inside a dielectric substrate is smaller than the actual angle of incidence in free space (\( \theta_d < \theta_{air} \)). This is shown in Fig 2.11. Accordingly, the \( \theta_d \) does not vary much with the change in angle of incidence, making the FSS structure less angle sensitive. The detailed work is done in reference [11, 23].

![Figure 2.11](image)

**Figure 2.11** Different FSS/ Dielectric arrangements (a) Frequency Selective Surfaces are embedded in dielectric substrates, \( \varepsilon_{eff} = \varepsilon_r \) (b) Frequency Selective Surfaces printed on a dielectric substrate, \( \varepsilon_{eff} = (\varepsilon_r+1)/2 \). The red and green lines represent the ray path of plane waves at different angle of incidence.
2.5.5 Angles Of Incident Plane Wave And Its Polarization.

The angle at which the FSS surface is being illuminated forms the basis of the spectral behavior of the FSS. The resonant frequency and the band edges should have consistent performance over a wide range of incident angles. However, the FSS performance is affected by the angle of incidence. As seen in Fig 2.12, when an incident signal arrives at an off-normal/oblique angle to a frequency selective surface in which the elements are separated by $s$, the width and the separation between the elements will be effectively reduced by factor $\cos \theta$. Therefore, the effective element dimensions seen and the currents induced in these elements differ with respect to the signal that arrives at the FSS at normal incidence ($\theta^o=0$) [36].

![Diagram of normal and oblique incident signal on FSS](image)

**Figure 2.12** Normal and Oblique incident signal on FSS. The separation $s$ between the elements changes with the angle of incidence and the equivalent projected separation distance becomes $s\cos \theta$.

As discussed in Section 2.2.2, the polarization of the incident plane wave is also important and must be analyzed separately for TE and TM cases.
2.6 PLANAR AND 3D FREQUENCY SELECTIVE SURFACES

Most research was directed to using a single surface, periodic metal-dielectric array in two-dimensional (2D) space. A number of methods are reported in the literature aimed at improving the characteristics of traditional 2D planar FSS. The three dimensional volumetric elements forming a periodic structure have gained some attention. Fig 2.13 shows an example of the geometry of two-dimensional tri poles [11] and three-dimensional clathrop FSS structures [18].

![Figure 2.13](image)

**Figure 2.13** (a) A two-dimensional planar array of tripoles. (b) A three-dimensional structure of clathrop [18].

Unlike the planar structures, a 3D FSS can provide greater design flexibility and a level of control on both electric and magnetic fields as they permit the flow of electric currents with components perpendicular to the surface. Theoretically, a multiple layered FSS can be generated from materials of similar properties, i.e. 3D structures can be synthesized from 2D structures which are strongly coupled by capacitive or inductive near fields [37]. A 3D cylindrical FSS architecture was developed from a 2D circular ring FSS
analogue in which the frequency and the band stop / band pass operation of the structure was tuned by the radius of the cylinder [38]. Azemi et al used the same concept of 3D FSS to improve the frequency stability over wide angles of incidence by tapering the FSS structure [39].

With continued growth of additive manufacturing and 3D printing techniques, new methods of fabricating 3D FSS have been explored. The 3D FSS has good stability for angle of incidence and different polarizations. However, these types of FSS are heavy, voluminous and mass production is time consuming and costly.

2.7 SINGLE AND MULTILAYER PLANAR FSS

A traditional single layer FSS is comprised of a two dimensional periodic array of shapes that are either printed on a supporting dielectric or etched through a conductive layer, as shown in Fig 2.14(a). These structures have found many applications in microwave, millimeter and optical wave parts of the electromagnetic spectrum [40].

An array of linear dipoles as FSS elements was among the first configurations to be analyzed. When illuminated with an electromagnetic plane wave, a small number of basis functions were required to synthesize the induced currents [41]. Single layer ring element arrays were studied because of their wider bandwidth [42]. With the closed packed arrays of rings, reflection bandwidth of 26% common to angles of incidence up to 45° was attained. This ring element was further modified and one additional concentric ring was added modifying the transmission curves [43]. The obtained transmission curves were more complex than the simple rings but the reflection and transmission bands were closely placed. A band centre frequency ratio of 1/1.3 was achieved by the array of concentric rings. However, the grating lobes start to appear beyond 45° angle of incidence. Parker et al
extended the study to examine the current distribution around the rings and the effect of changes in lattice and element geometry. The elements were arranged first in a square lattice and then in triangular lattices. The triangular lattice arrangement leads to closely packed elements and therefore broader bands were achieved [44]. Various other FSS elements like the Jerusalem cross ring, tripod, crossed dipole and square loop have been studied in a single layer configuration [45].

The filtering response of a single layer resonant FSS suffers from narrow bandwidth for high inductance and low capacitance designs (discussed in Chapter 4, Section 4.2.3). The most common technique to increase the bandwidth and improve the filtering response is by adding multilayers with the inclusion of dielectric spaces [22]. These multilayer planar FSSs have the same geometry elements with the same dimensions, have closely spaced transmission/reflection bands, and have wider bandwidths as compared to single layer arrays [46, 47]. The shape of the element and the lattice configuration, including the interlayer coupling are important parameters in achieving the required performance in a specific application. By cascading two or more FSS screens with the Koch fractal element, an increase of 38% in bandwidth was achieved when compared to the bandwidth obtained with a single FSS screen element [48]. Many FSS-Dielectric configurations are possible forming the multilayer FSS structure, as shown in Fig. 2.14.
Figure 2.14 Patch type FSS structures showing layer configurations (a) Single Layer FSS printed on substrate. (b) Double layer FSS printed on each side of substrate. (c) Single layer FSS sandwiched between two slabs of substrate. Thickness and dielectric constant of the slabs determines the change in resonant frequency of the FSS structure [11].

Multilayer FSS have helped solve several antenna challenges. A reconfigurable printed dipole array backed by a FSS screen controlled the phase of the reflected waves to achieve a broadband operation [49]. Erdemli et al found that the bandwidth was enhanced when the FSS elements were brought closer within the layers. He also demonstrated that if the reflection coefficient phase of the FSS was maintained near 0°, the FSS served to emulate a magnetic ground plane. One more method for the extension of the operating bandwidth of a wideband antenna on top of a metallic reflector was presented by Marco [50]. An additional reflection plane for a higher frequency band was created by
sandwiching the FSS between the antenna and the ground plane. The bandwidth was tuned by stacking multiple layers of FSS [51]. These FSSs can be used as a reflector for many planar ultra-wide band antennas. Several applications require wideband performance as well as a flat top transmission response. This has been achieved using bi-dimensional FSS configurations like the cross, square loop [52], and the cross dipole and ring [53] on opposite sides of the substrate.

The effect of a substrate on a screen perforated with circular apertures [54] or crossed dipoles [55, 56] showed that as the dielectric thickness increases from zero to about one eighth of a wavelength, the resonance decreases rapidly. A frequency limit was achieved in each of them which differed depending on the dielectric and configurations. The influence of the substrate on the reflection / transmission band ratios of a thin substrate showed increase and honeycomb sandwich structures showed the cyclic variation over the range of layer separations [57]. A detailed review on the influence of dielectric layers on the performance of FSS was done by Callaghan et al [23]. The studies included a modal analysis as well as the experimental work of the slot and patch dipole elements when embedded within or bonded to the surface of a substrate. The dielectric tuning effect was illustrated in terms of contours of transmission loss for slot arrays as functions of frequency and thickness. In addition to the mechanical considerations, the dielectric constant of the dielectric substrate is equally important.

A supporting dielectric layer of higher dielectric constant is preferred for low resonant frequency in order to achieve better angular stability and smaller element dimensions [58]. The use of high dielectric substrates has drawbacks of high transmission loss and narrow bandwidths. For the applications like stealth radomes, the dielectric slabs of low dielectric constant and high specific strength were used [59, 60]. When thick FSS
screens were adopted for radome applications, the thermal mismatches between metal and composite materials were high and the total weight increased significantly.

2.8 SIMPLE AND COMPLEX FSS

Simple element structures like circular loops and square patches have been investigated in detail [11]. These structures were relatively easy to design and manufacture without the need for tight tolerance control. However, these structures have single band resonance and in many communications situations, closely spaced multiband resonance is required. This can be achieved by modifying these simple structures in terms of fractal or convoluted geometries miniaturizing the overall element size. For better understanding, an example of square patch FSS element with modifications is shown in Fig 2.15.

![Figure 2.15](image)

(a) (b) (c)

*Figure 2.15* Broadband elements based on modifying the square patch type FSS. (a) Basic square patch (b) Self-similar square patch fractals (c) Closely packed convoluted deviations.

Fractals are defined as the self-similar geometrical shapes which can generate more complex shapes by iterating simple geometries. For example the space between the resonant elements in an FSS can be reduced by fractal Hilbert curves [61]. This curve was drawn in a way that it eventually passes through every point in a square. This design procedure has assisted in reducing the unit cell areas and larger values of figure of merit.
(resonant wavelength / periodicity) implying smaller cell size. A similar concept has been
used in designing a miniaturized prefractal monopolar antenna for 3.4 – 3.6 GHz Wi Max
band [62].

The self-similar fractal elements were used by Douglas in [63] for the design of
multiband frequency selective surfaces. The separation of bands can be controlled by
choosing the appropriate scaling used in the fractal crossbar screen elements. In addition,
multiband and wideband behavior in small antennas can also be achieved using self-similar
fractals of FSS [64-68]. An alternate approach is to convolute or fold the element track
giving a greater resonant length. A convoluted linear dipole was used to derive an array
with greatly reduced unit cell size for use on curved surfaces or at long wavelengths. These
modified structures were also capable of controlling the separation of useable reflection
bands from the grating lobes [33, 69]. Highly convoluted structures like interwoven single
layer cross dipoles have been developed to improve the fractional bandwidth and the
fundamental band width [70].

Whether it is a fractal FSS or a convoluted FSS structure, the conductor length
increases keeping the physical unit cell size the same thereby miniaturizing the overall FSS
structure. The dimensions of the unit cell should be small, compared to the operating
wavelength, in order to achieve angular stability [71]. As compared to the conventional
FSS structures based on half wavelength resonance, the miniaturized FSS elements can
incorporate many more unit cells in a finite area. Therefore, miniaturized FSS are an
attractive option in a finite area as they show similar properties to that of infinite FSS
structures. These structures also find application in conical radome application due to less
distortion of the transmission response, and in artificial magnetic conductors to facilitate
flexible spatial filtering [72].
2.9 METHODS OF ANALYSIS OF FREQUENCY SELECTIVE SURFACES

The performance of a frequency selective surface broadly is described by its plane wave scattering parameters namely $S_{11}$ (the reflection coefficient) and $S_{21}$ (the transmission coefficient) [73]. When an electromagnetic wave interacts with the FSS, a part of it is transmitted and part of the energy is reflected. Several techniques have been developed to calculate the scattering parameters associated with frequency selective surfaces. These include the computational codes such as Method of Moments (MoM) [8], the finite element method (FEM) [74], the finite–difference time domain (FDTD) method [75], and the equivalent circuit (EC) method [25].

A commercial package, CST Microwave studio, is used in this research to design and analyze FSS of simple and complex geometries. CST uses the finite integration method which is a variant of the FDTD method, to simulate the electromagnetic field scattered by FSS structures. The detailed discussion and investigation on how reliability and accuracy of results is achieved is found in Chapter 4, 5, 6. These computational codes will not be discussed in detail here as the equivalent circuit method was used in only a few of the FSS designs. A brief discussion about this technique is included in the section below:

a) Equivalent Circuit (EC) Model

An equivalent method of analyzing a frequency selective surface is drawing its equivalent circuit model. This method is based on the transmission line analogy and approximates the frequency selective surface as a lumped element network. Unlike intensive computational approaches like FDTD, FEM, the EC model provides the physical insight into the working principles of frequency selective surfaces. In the analysis of periodic structures where the element (metallic part) shows the inductive behavior and the
inter element space shows the capacitive behavior, three different fundamental regions are recognized. At long operating wavelengths when the periodicity \((D)\) of FSS unit cell is much smaller than the operating wavelength \((\lambda_g)\) (i.e. \(D \ll \lambda_g\)), the periodic surface is analyzed using homogenization theory. And this region is called quasi-static regime and the calculations of the inductance and capacitance can be accomplished by averaging the currents flowing on the FSS \([76]\). However, the equivalent circuit model is more useful in analysis of simple FSS geometries and linearly polarised surface when the periodicity is smaller but comparable with the operating wavelength (i.e. \(D < \lambda_g\)). And the last region is where the grating lobes are due to the periodicity of FSS elements being large than the operating wavelength (i.e. \(D > \lambda_g\)).

Many researchers have followed this circuit approach for FSS analysis and developed formulas capable of adequately reproducing the properties of FSS, details can be found in \([77]\). These EC start to fail initially when the dielectric substrate and the angle of incidence are taken into account. For this reason, Langley *et al* tried to derive analytical relations for complex elements like ring, a double ring, cross, Jerusalem cross \([25, 78, 79]\). More accurate models based on multimode formulation for thin substrates \([80]\) and multilayer FSS \([51]\) are developed. A brief summary of some of the significant FSSs, comparison of their resonant behavior and description of their physical parameters are given in Table 2.4.
Table 2.4 A summary of some significant FSS structures.

<table>
<thead>
<tr>
<th>Ref.</th>
<th>Authors</th>
<th>$f_r$ (GHz)</th>
<th>BW (GHz)</th>
<th>Unit cell</th>
<th>Substrate thickness</th>
<th>Loss at attenuation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>J. Huang, T. K. Wu, and S. W. Lee</td>
<td>8.4</td>
<td>3.5</td>
<td>0.2$\lambda_r$ x 0.2$\lambda_r$</td>
<td>6mm</td>
<td>-55dB</td>
<td>A single and double screen of circular rings for a triband system. Dielectric loading effect is used to reduce the ring size and element spacing.</td>
</tr>
<tr>
<td>11</td>
<td>R. Mittra, C. H. Chen, and T. Cwik</td>
<td>12.7</td>
<td>1.5</td>
<td>0.05$\lambda_r$ x 0.05$\lambda_r$</td>
<td>10mm</td>
<td>-</td>
<td>Number of representative techniques for analyzing FSS (patches and apertures) in conducting screen are presented. Basic FSS properties approaches to predict the frequency response and their important applications. Truncated, curved and double periodic screens are measured and discussed.</td>
</tr>
<tr>
<td>19</td>
<td>D. S. Lockyer, J. C. Vardaxoglou, and R. A. Simpkin</td>
<td>13.2</td>
<td>1.4</td>
<td>0.17$\lambda_r$ x 0.17$\lambda_r$</td>
<td>0.07mm</td>
<td>-2dB</td>
<td>Plane wave transmission response and angular stability of a complementary FSS structure were analyzed.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>13.8</td>
<td>1.6</td>
<td>0.13$\lambda_r$ x 0.13$\lambda_r$</td>
<td>0.07mm</td>
<td>-2dB</td>
<td></td>
</tr>
<tr>
<td>23</td>
<td>P. Callaghan, E. A. Parker, and R. J. Langley</td>
<td>20</td>
<td>0.2</td>
<td>0.5$\lambda_r$ x 0.5$\lambda_r$</td>
<td>0.02mm</td>
<td>-2dB</td>
<td>Linear dipoles embedded within and bonded on substrate layer were investigated. Influence of trapped waves, frequency pulling effect, shape of passband and sensitivity to angle of incidence was reported.</td>
</tr>
<tr>
<td>34</td>
<td>C. Mias, C. Tsakonas, and C. Oswald</td>
<td>1.9</td>
<td>0.6</td>
<td>0.02$\lambda_r$ x 0.02$\lambda_r$</td>
<td>4mm</td>
<td>-0.5dB</td>
<td>Hexagonal passband FSS elements are engraved in the metallic coating in energy saving windows covering GSM and GPS frequencies leading more efficient radio frequency management.</td>
</tr>
<tr>
<td>Page</td>
<td>Authors</td>
<td>Parameters</td>
<td>Transmission/Reflection Change</td>
<td>Remarks</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>------</td>
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<td>------------</td>
<td>-------------------------------</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>38</td>
<td>S. N. Azemi, K. Ghorbani, and W. S. T. Rowe</td>
<td>$0.01\lambda_r \times 0.01\lambda_r$, 10mm, -42dB</td>
<td>A 3D cylindrical FSS changes from stop band to pass band at certain length. A dielectric filling of cylinder leads to close transmission/reflectio n bands.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>51</td>
<td>Y. Ranga, L. Matekovits, A. R. Weily, and K. P. Esselle</td>
<td>$0.5\lambda_r \times 0.5\lambda_r$, 15mm, -50dB</td>
<td>A compact low profile FSS for ultra-wide band applications can be used as a shield for UWB antenna and the nearby conducting surfaces commonly focused in modern microwave and wireless devices.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>61</td>
<td>E. A. Parker, and A. N. A. El Sheikh</td>
<td>$0.25\lambda_r \times 0.25\lambda_r$, 0.02mm, -30dB</td>
<td>The concept of convoluting a square loop in few stages to diminish the size of the unit cells.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>71</td>
<td>K. Sarabandi, and Nader Behdad</td>
<td>$2.2\lambda_r \times 2.2\lambda_r$, 0.5mm, 0dB</td>
<td>A double layer bandpass FSS comprised of miniaturized elements comprising of resonant dipole and slot elements. Printed circuit board technology is used for fabrication of prototype.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>81</td>
<td>F. Bayatpur, and K. Sarbandi</td>
<td>$0.83\lambda_r \times 0.83\lambda_r$, 0.125mm, 0dB</td>
<td>A miniaturized element passband FSS produces high order response by establishing proper coupling between the inductive and stop band surfaces on either side of a single layer substrate.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>82</td>
<td>G. Yang, T. Zhang, W. Li, and Q. Wu</td>
<td>$0.06\lambda_r \times 0.06\lambda_r$, 1.6mm, -5dB</td>
<td>A bandpass miniaturized FSS with better miniaturization performance, stable performance with different polarizations and plane wave incident angles.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*where $\lambda_r$ is the resonant wavelength corresponding to the FSS resonant frequency.*
The aim of this research is to design a frequency selective surface with small unit cell but with attenuation that is not achieved by any of the FSS structures mentioned in Table 2.4. The novel use of screen printing is made in fabrication of FSS in this work. Detailed study is done in the following chapters.

2.10 SUMMARY

Frequency selective surface (FSS) is a regular array of identical resonant unit cells designed to reflect, transmit or absorb electromagnetic wave fields as a function of frequency. These structures have been investigated over the years for a variety of applications based on their diverse filtering performance. In this chapter, a comparative study and general theory of conventional elements in design of frequency selective surfaces were presented. The fundamental understanding of elementary principles, filtering properties and physical understanding of grating lobes associated with every frequency selective element were explained. The resonances and the operation mechanism of these structures are based on the element geometry, conductivity of the elements, the super or substrate material and the plane wave polarization and incidence angles. A brief overview of past work done in this area was also included in this chapter. The research includes the basic understanding of a simple dipole (slot or patch) as a filtering device to the more complex FSS elements. A dipole forms the foundation element of all other resonant structures like cross dipoles, square loops, Jerusalem cross, meanders etc. Following that, the significance of designing convoluted or multi-layer FSS structures in order to broadband spectral response of these structures was presented. The new approach of designing volumetric structures like 3D FSSs using additive manufacturing techniques was briefly discussed. The absorption properties have been explored in order to reduce the RCS (Radar
Cross Section) of mounted antennas in warships and other military applications. Methods of analyzing these conventional FSSs were briefly also discussed.
2.11 REFERENCES


CHAPTER 3

MODELLING, FABRICATION AND MEASUREMENT

3.1 INTRODUCTION

This chapter describes the modelling procedure, fabrication technique and the measurement set up used for analyzing thin flexible frequency selective surfaces. The modelling is based on the finite integration method in the frequency domain. This method is particularly efficient for electrically small and thin structures. This solver also proves to be faster in calculating the scattering parameters for strongly resonating structures. The screen printing fabrication is discussed in detail and the prototypes made are included in Chapter 4, 5, 6. Finally, the experimental set up for measurements of the frequency response is discussed.

3.2 SIMULATION ANALYSIS

The mode matching techniques used for analysis of FSS were first applied in waveguides with varying cross section. Partly based on the transmission line principles, the mode matching method described the FSS behavior in terms of approximate methods using equivalent circuit analysis [1]. Because of the limited computational resources, the mode matching technique had limited modelling capabilities resulting in less accurate equivalent circuits. More accurate numerical methods like methods of moment (MoM), finite element method (FEM), and finite difference time domain method (FDTD) came into use to study
and analyze FSSs. In recent years, commercially available software has been used in the analysis and design of FSS, e.g. CST Microwave studio®, Ansoft Designer®, and Ansoft HFSS®.

In our research, we modelled FSS structures using CST Microwave studio which uses a full 3D wave simulation tool based on the finite integration technique (FIT), which discretizes Maxwell’s field equation in the integral form.

### 3.2.1 Unit Cell Modeling

The FSS structures were assumed to be flat and infinite arrays. In CST Microwave studio, the array is simulated using unit cell boundary conditions. The relationship between the two opposite sides of the unit cell was done by defining the phase shift so that the calculation domain carries the simulation periodically in the $x$ and $y$ direction. If one boundary of the unit cell is changed, the three other boundaries will also change. The incident plane wave is expanded using Floquet modes and the boundary perpendicular to the unit cell ($z$-direction) was left open. Transient and frequency domain solvers both use finite integration technique which works on the integral formulation of the Maxwell equations. A key application of frequency domain solver is periodic structures like PBGs, FSSs or phased arrays. The frequency domain solver is used for electrically small structures like the FSS structures designed and modelled in this thesis with small dimensions in millimetre range. Also the unique feature of switching from Cartesian to tetrahedral meshing in frequency domain solver leads to high accuracy and speed.

Thus frequency domain solver was used to simulate the FSS structures. This solver has an advantage of solving the problem for a single frequency within the mesh limit and also multiple frequencies in a sweep. The computational volume is discretized onto a mesh
and the s-parameters are calculated. The size and type of mesh, whether a hexahedral or tetrahedral volume, play a crucial role in simulation speed, memory and accuracy. In this research, a tetrahedral mesh was used for quick and accurate simulations. Fig 3.1 shows the unit cell comprising multiple dipole elements. The surrounding eight elements are adjacent elements repeated to infinitely in both the \( x \) and \( y \) axes. The \( x \) and \( y \) boundaries were chosen to be the unit cell and the \( z \) boundaries (\( z_{\text{min}} \) and \( z_{\text{max}} \)) were left open.

![Diagram of an infinite dipole array](image)

**Figure 3.1** An infinite dipole array modelled as a unit cell carrying a dipole and the applied boundary conditions in \( x \), \( y \) and \( z \) axis. The dotted line shows the unit cell area considered for simulation.

Apart from the boundary conditions, the mesh refinement analysis is also important. It identifies the areas of the FSS geometry that are critical to the electromagnetic behavior of the structure. However, the complex dense FSS structures need significant mesh definition at the areas of metallic pattern as compared to a simple FSS structure. Thus, long computational time (many hours) is required in simulating these structures. The choice of frequency range over which the FSS structure is simulated also has a strong influence on
the computational time. Therefore, the frequency range of interest should be chosen wisely in order to limit the computational time to reasonable amounts.

3.3 SCREEN PRINTING

The electronics industry is slowly moving towards printed electronics on flexible substrates, and low cost volume fabrication of circuits. The most commonly used methods of manufacturing flexible electronics are inkjet printing and screen printing. Inkjet printing is a type of digital printing in which the digital image is reprinted by depositing the ink droplets onto the plastic, paper or any other substrate. Due to the problems with poor long term durability and nozzle clogging issues, inkjet printing is restricted.

Screen printing is a mesh based stencil technique used to print the conductive ink on the substrate. The process has fewer initial steps compared to traditional circuit board printing. The major advantages are flexibility of the printed conductive tracks and lower set up cost for manufacture. However, the conductor functionality and printability can interfere with each other; therefore, careful optimization of the designs was necessary. The liquid properties of conductive ink such as viscosity, surface tension and solids content must be tightly controlled. The screen printing techniques were used in this research.

3.3.1 APPLIED CONDUCTIVE INK

The conductive polymer silver ink Electrodag 479SS provided by Henkel Acheson Ltd as shown in Fig 3.2 was used. The uncured silver paste has solid content of 74% by weight and the dry ink thickness is 12 µm. The viscosity of this paste is 1200 mPa-s and the density is 2.56 kg/lt. The electrical conductivity is $4.3 \times 10^6$ S/m at room temperature and the curing schedule is 15 minutes at 90°-93°C. One of the attractive features of this ink was the excellent fine line printing ability, which our miniaturized complex designs require. Other
characteristics of this ink include fast drying, excellent abrasion resistance and hardness, very low sheet resistance and good adhesion with the printable films [2].

Figure 3.2 Conductive silver paste used for printing.

3.3.2 FLEXIBLE SUBSTRATE

The substrate used in this research was thin polycarbonate film. Polycarbonate films are impact resistance, high-gloss surfaces with high temperature resistance, excellent dimensional stability, excellent printability and high transmission. The film is supplied with protective masking on both sides. The film is available in different thicknesses ranging from 0.2 mm – 2 mm. In our research, a 0.2mm thin polycarbonate sheet was selected to achieve the maximum flexibility of the FSS screen and each sample was approximately 25 cm x 28 cm in dimension, as shown in Fig 3.3. Unlike other plastic films, this film does not require any surface pretreatment before printing. Since the polycarbonate film can withstand high curing temperatures of about 120°-130°C, the stability of these films allows better curing of the FSS pattern.
Figure 3.3 Substrate: (a) Polycarbonate samples of 0.2 mm thickness (b) Rolled in sheets because of flexible nature.

3.3.3 SCREEN PRINTING STENCIL

A stencil screen was made of mesh stretched over an aluminum frame (see in Fig 3.4). The mesh can be a traditional silk or most commonly, used polyester. In our research, we used a tightly woven polyester mesh screen which carries the stencil on which a thin layer of conductive ink was spread to produce the original image. Simple FSS designs were easy to screen print, whereas for complex designs, scaling the mesh of the screen was necessary. The mesh size determines the particle size required for the granular ink to pass through. For simple FSS structures 0.3 mm (50T) sieve size was used, whereas for complex designs with smaller line widths, the 100T mesh was used. The screens were designed from a .pdf file of the original image and were manufactured by Gabba Screens. Ltd, Brisbane in a rigid aluminum frame.
The manual screen printing of FSS involves applying the ink using an applicator called squeegee. The squeegee has a flat top and a soft blade. It is made of a high quality polyurethane and is available in different grades such as 60, 70, 80 durometer. The squeegee hardness grade determines the pressure required to push ink through the mesh. The softer the squeegee, the thicker is the ink deposited on the substrate, and similarly the harder the squeegee the finer the ink pattern on the substrate. The grade 70 durometer squeegee was used in this fabrication process. These screens were reusable; the image patterns were removed from the frame and replaced by different patterns.

![Figure 3.4 A screen stencil with padding on the edges and the 70 durometer squeegee.](image)

**3.4 PROTOTYPE FABRICATION**

There are three major steps involved in fabricating the FSS. The same procedure was used for all the fabricated prototypes. Fig 3.5 gives the illustration of the fabrication process.
STEP 1: Alignment of FSS sample and screen

Before printing commenced, the substrate was placed on an aluminum backing plate with four small pegs at the four corners for registration of the substrate, as shown in Fig 3.6 (a). Adhesive tape was used to fix the substrate onto the backing plate, so that it stays flat and intact during the printing process. The backing plate was centered on a large wooden backing wooden board functioning as a workbench. The stencil screen was laid on top of the substrate and properly aligned, as shown in Fig 3.6 (b). In order to have the perfect print the “snap” gap between the mesh screen and the substrate is required. This gap of approximately 5-7 mm and was maintained by including some padding of equal thickness on the sides of the stencil frame. The gap ensures that when the squeegee applies pressure on the screen and substrate, the screen springs back up as pressure is removed to avoid smudging of ink.
Figure 3.6 Alignment of the screen-printing set up (a) a flat wooden working bench with aluminium backing plate 25 cm x 28 cm in dimensions as printing base of the sample (b) laying of mesh screen on the substrate.

**STEP 2: Application of ink**

With the frame on top of the substrate, a thin line of conductive ink was spread horizontally on one edge of the inner side of the stencil region (FSS image), as seen in Fig 3.7 (a). Holding the frame above the substrate, the ink was spread evenly using the squeegee, covering the entire FSS pattern. Then the frame was lowered and the conductive ink was pressed through the stencil by scraping the ink from one edge to other using the squeegee, as shown in Fig 3.7 (b). The pressure effectively fills the mesh openings with ink and moves the ink on the front side of screen, depositing the intended pattern on the substrate surface. The squeegee was angled at 60° with respect to the screen for consistency.
STEP 3: Curing the ink

Proper drying and airing of ink is critical for the ink tracks to be properly conductive. In order to avoid rapid drying which may cause the surface of ink to skin, the prototype was left for 4 mins at room temperature to prevent smearing of the ink, and then cured in an oven for 15 mins at $90^0-93^0$C, as shown in Fig. 3.8. The curing conditions (time and temperature) depend on the curing equipment, oven loading and the oven temperature [2].
Figure 3.8 Drying and curing of ink. The sample placed in oven at the temperature of 93°C.

The conductive ink on the screen dries within minutes. This may block the mesh, so a quick and thorough wash with solvent was required using the blend of 25% Carbitol acetate and 75% Methylethylketone (MEK).

3.5 MEASUREMENT SET UP

The measurement of the plane wave transmission through FSS was carried out in free space in a microwave anechoic chamber. Standard horn antennas were used which were fixed and facing each other, each connected to a vector network analyser (VNA) interfaced for S-parameter measurements. The FSS sample under test was placed between the antennas, one transmitting the signal and other receiving it. For oblique angle measurements, the FSS holder was rotated to the angle of interest. The schematic diagram and the actual experiment set up are shown in Fig 3.9. The experimental arrangement must satisfy far field requirements and the FSS must block a significant proportion of the main beam.
The calculations that need to be done prior to the measurements are given as below:

(a) **Far field calculations**: The transmitting and the receiving antennas are typically separated by a distance sufficiently large to simulate a plane wave operating environment, as shown in Fig. 3.10. The wave radiated by a source is spherical in shape with the wave fronts expanding outwards at a rate equal to phase velocity, $v_p$, or the speed of light in the case of free space. The receiving antenna is said to be in far field or far zone, when the distance between the two antennas is large enough so that the wave front across the receiving aperture may be considered as a plane wave. In order to ensure that the FSS lies in the far field region of the two antennas, the following formula is used [3]:

$$d_{\text{far field}} \geq \frac{2D^2}{\lambda_r} \quad (3.1)$$
where $d_{\text{far-field}}$ is the allowable distance between the antenna and FSS, $D$ is the largest linear dimension of the radiating aperture and $\lambda_r$ is the resonant wavelength.

![Figure 3.10](image)

**Figure 3.10.** Far-field region of the two horn antennas where $d_{\text{far-field}}$ is the longest linear dimension of the radiating aperture.

**b)** **Beamwidth:** It is the next important parameter which needs to be calculated. The beamwidth is defined as an angle between the half power (-3dB) points on the main lobes of the antenna radiation pattern.

![Figure 3.11](image)

**Figure 3.11** Half power beam widths $\beta_{xz}$ and $\beta_{yz}$ in the two principle planes $xz$ and $yz$ plane respectively. The tangential component of the two beam angles gives the 3 dB area covered.
The beamwidth in two principal axes namely $xz$ plane (horizontal beamwidth) and $yz$ plane (vertical beamwidth) are calculated using the following equations [3]:

$$\beta_{xz} = 0.88 \frac{\lambda}{l_x}$$ (3.2)

and

$$\beta_{yz} = 0.88 \frac{\lambda}{l_y}$$ (3.3)

where $\beta_{xz}$ is the horizontal beamwidth, $\beta_{yz}$ is the vertical beamwidth, $l_x$ is the width and $l_y$ is the height of the horn antenna aperture. Furthermore, the 3dB area covered in $xz$ and $yz$ plane can be derived from the tangential component of the beam angle shown below:

$$\tan \beta_{xz} = \frac{s_1}{d_{far\ field}}$$ (3.4)

and

$$\tan \beta_{yz} = \frac{s_1'}{d_{far\ field}}$$ (3.5)

where $S_{xz} = 2S_f$ and $S_{yz} = 2S_f$ give the area covered by the half-power beamwidths $\beta_{xz}$ and $\beta_{yz}$ respectively for the horn antenna shown in Fig. 3.11.

The measurement was performed in two steps: (a) calibration was achieved by eliminating the losses in the cable and foam by measuring the $S_{11}$ (reflection) and $S_{21}$ (transmission) between the two horns without the sample. This is considered as the reference value (also called thru calibration). (b) The measurement was repeated to account for diffraction around a metal sheet. A blank sample with the same size as the sample was measured in dB and subtracted from the subsequent sample measurements.

### 3.6 SUMMARY

In this chapter a brief discussion about the modelling of the FSS using the commercial electromagnetic simulation tool (*CST Microwave studio 2013*) is included. This approach allowed parametric studies of the performance of the various FSS structures.
The unit cell boundary conditions were based on the Floquet principle so every unit cell in an infinite FSS contains exactly the same currents and fields. The flexible films were fabricated using screen-printing. To demonstrate the validity of FSS prototypes, a free-space measurement technique was used. Flexible passive FSS can be rolled out in sheets as a mass produced product and can be attached to any arbitrary target material.
3.7 REFERENCES


CHAPTER 4

SINGLE LAYER PLANAR FREQUENCY SELECTIVE SURFACE

4.1 INTRODUCTION

This chapter deals with the modelling, analysis and the plane wave transmission/reflection response of a planar, single-layer FSS. A simple ring shaped element was used for analysis and some of its primary features are outlined in the beginning of this chapter. A grid lattice array of silver rings was screen printed on a thin polycarbonate substrate. The plastic substrate material is available in thin, flexible and highly transparent grades. The FSS structures of the ring and split ring resonators have been studied previously, but to the best of our knowledge, the design of a ring resonator on a thin flexible optically transparent substrate is novel. The unit cell dimensions of the ring element was approximately $\frac{\lambda_0}{3}$. The angular and polarization stability of the ring FSS over normal and oblique angles makes them valuable for shielding applications where the angle of incidence is unknown. The detailed design and the physical specifications of a miniaturized ring resonator array on a single dielectric layer was investigated. This FSS model acts as a reflector and blocks the transmission at 12.5 GHz. To validate this concept, an FSS was manufactured and measured. Good agreement between measured and simulated results supports the viability of polycarbonate film as a backing substrate. The influence of
polarization, incidence angle, substrate permittivity and substrate thickness on the transmission stop band and bandwidth also presented.

Large unit cell sizes have been used in FSS operating at lower frequency bands. The filtering capacities and applications for various high frequency structures demand a higher density of elements and a smaller unit cell size. An attempt was made to design a planar FSS on a thin dielectric material with a low relative permittivity, without compromising the size of the unit cell. Section 4.4 and subsequent sub sections of this chapter the effect of miniaturizing the FSS element to reduce the cell size area and improve the angular stability of the FSS. The miniaturization of a square loop FSS using meanders to fill the unit cell space is presented. This structure is a single layer interwoven structure with loop type elements and a stop band transmission notch in s-band at 2.2 GHz. The dimensions of the square element are smaller than $\lambda_o/12$, with $\lambda_o$ be the operating wavelength.

The meandered lines used were formed using triangular peaks instead of the more standard rectangular steps in order to have maximum possible reduction in size and maximum interweaving between the adjacent elements of the array. The flexible, thin and transparent nature of this surface makes it suitable for application on flat or curved surfaces on windows and walls in order to create a radio secure environment. Due to the flexibility of this FSS structure, the bulk production in long sheets is easy, the screen can be semi-transparent at optical frequencies and the fabrication cost is relatively small as compared to the traditional fabrication techniques. The latter half of this chapter includes the design approach and plane wave transmission response of the single layer miniaturized FSS. The chapter concludes with a case study of the FSS on glass and the effect on transmission response.
4.2. PASSIVE STOP BAND RING RESONATOR

4.2.1 Ring Elements on a Dielectric Substrate

A uniform planar FSS structure comprising of circular loops / ring resonators was considered for analysis. The choice of the ring elements is based on a few key features of these planar structures such as: (1) simple to manufacture; (2) production cost is low; (3) compatible with standard planar printing technologies [1]; (4) less sensitive to wide angles of incidence than other simple element shapes [2]; (5) electrically small unit cell. The geometry of the elements and the periodic properties of the array largely determines the centre frequency and bandwidth of the stop band. When the FSS structure comprising metallic rings is printed on a dielectric substrate (capacitive FSS), the incident wave is reflected at the resonant frequency. The FSS structure consisted of a square lattice of metallic rings printed on a thin polycarbonate substrate.

4.2.2 FSS Design Specifications

For a free standing ring element (see Fig 4.1), the resonant frequency is given by [3]:

\[ f_r = \frac{c}{\lambda_r} = 2\pi (R_{in} + 0.5b) \]  \hspace{1cm} (4.1)

where \( R_{in} \) is the inner radius of the ring, \( b \) is the thickness of the track, \( f_r \) is the resonant frequency and \( \lambda_r \) is the wavelength at which transmission is blocked. The element width \( b \) is smaller than its length in most cases. When a dielectric substrate is introduced, the air-dielectric interface is replaced by an effective dielectric. The dielectric substrate affects the response by lowering the resonant frequency and changes the bandwidth as well. A more detailed discussion on the effect of the dielectric permittivity on the resonant behavior of the FSS is given in Section 2.5.4.
An array of circular loop/ring resonators in a square lattice backed with plastic (polycarbonate) substrate with \( \varepsilon_r=3.2 \) and thickness of 0.21mm is shown in Fig 4.1(a). The solid ring denotes the presence of metal which is silver Electrodag 479SS, with ink conductivity of \( 4.3 \times 10^6 \) S/m. The ring width was kept small in order to ensure the optical transparency of the FSS, as the ink is opaque. The square frame shows the unit cell of the FSS structure (see Fig 4.1(b)). Table 4.1 gives the physical dimensions of the FSS element for stop band transmission performance.

Figure 4.1. (a) Ring resonator array in xy plane. For oblique angles the orientation of E and H plane changes with respect to the direction of wave propagation and gives rise to TE (\( E_\perp \)) and TM (\( E_\parallel \)) mode (b) FSS Unit cell. (c) Equivalent circuit model.
Table 4.1. Physical dimensions of FSS Ring Resonator.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Description</th>
<th>Dimensions (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$w$</td>
<td>Unit cell size</td>
<td>7.53</td>
</tr>
<tr>
<td>$d_j$</td>
<td>Out ring diameter</td>
<td>6.73</td>
</tr>
<tr>
<td>$b$</td>
<td>Thickness of ring</td>
<td>0.51</td>
</tr>
<tr>
<td>$s$</td>
<td>Spacing between rings</td>
<td>0.8</td>
</tr>
<tr>
<td>$t$</td>
<td>Track ink thickness</td>
<td>0.01</td>
</tr>
</tbody>
</table>

4.2.3 Theory of Operation

The conducting ring introduces a self-inductance due to the flow of charge in the loop and the coupling between the adjacent loops lead to mutual inductance. Similarly, the charge distribution across the small gap between the adjacent rings creates capacitance. The combined effect of this capacitance and inductance produces a low impedance surface near its resonant frequency, producing the stop band region in which the plane wave transmission through the structure is blocked, and the magnitude of the reflection coefficient approaches unity. The Fig 4.1(c) gives the equivalent circuit model of the ring unit cell. The resonant frequency, $f_r$, of the ring in terms of the inductance, $L$ and capacitance, $C$ is given by the equation:

$$f_r = \frac{1}{2\pi\sqrt{LC}}$$  \hspace{1cm} (4.2)

According to the lumped LC model, decreasing the gap width $s$ between two adjacent rings increases the capacitance, which in turn reduces the stop band frequency. An
increase in the inner diameter of the ring decreases the track width of the ring, increasing the path for the flow of current and therefore the inductance increases and lowers the stop band frequency. These are the general rules used for designing ring resonators [4, 5]. In order to avoid the scattering of energy in undesirable directions, the spacing of the repeating element was less than the shortest wavelength for the normal incidence (0° incident angle) in the operating band. For large incident angles like 45°, the repeating element spacing should be half the free space wavelength in order to avoid the grating lobes. Following this general rule, the FSS elements were placed in a square lattice spacing following the equation 2.4. For an incident angle (θ) of 0°, $\frac{W}{\lambda}$ needs to be less than 0.327. A smaller ring diameter ($d_1$) results in a higher resonant frequency and a smaller unit cell size ($w$) ensures good frequency response with varying incident angles [6].

The performance was studied using CST Microwave Studio using full wave methods. The ring FSS array was assumed to be flat and of infinite extent. The thermal conductivity, $\kappa$ of the polycarbonate is 0.22 Wm$^{-1}$K$^{-1}$ and relative permittivity, $\varepsilon_r = 3.2$. The directions of periodicity ($x$, $y$ directions and fields expanded as a set of Floquet ports) allow a rapid and accurate simulation in CST Microwave Studio. The prototype was manufactured using the screen printing technique previously discussed in Chapter 3.

4.3 SELECTIVE TRANSMISSION RESPONSE.

4.3.1 Simulation and Experimental Results.

The frequency response was measured using two standard microwave horn antennas as described in Section 3.5. The transmitting antenna was placed 70 cm from the FSS and the receiving antenna was placed 70 cm from the FSS under test. The set-up was calibrated for reflection ($S_{11}$) and transmission ($S_{21}$) response. The reflection calibration was achieved
by using a flat metal sheet of the same size as the FSS sample. The metal sheet was positioned on a foam stand with a convoluted foam absorber behind to prevent stray reflections, as shown in Fig. 4.2. The transmission calibration was done by removing the metal sheet and measuring the transmission from the transmit antenna, through the foam support to the receive antenna. The diffraction around a metal sheet was recorded and subtracted from the subsequent FSS transmission measurements (isolation). A vector network analyzer connecting the two horn antennas was used to obtain $S_{21}$.

![Figure 4.2](image)

**Figure 4.2.** The transmission and reflection measurement set up showing the ring resonator FSS fixed in a foam frame between two horn antennas. The middle picture shows the flexible and conformal nature of FSS. The size of the prototype screen is 28 cm x 26 cm.

Fig 4.3 shows the $S_{21}$ and $S_{11}$ for the FSS. The simulated and measured $S_{11}$ and $S_{21}$ results show a good agreement. The scattering parameters $S_{21}$ (experimental and simulation results) show the band stop characteristics centered at 12.5 GHz frequency (Fig 4.3). The maximum difference in $S_{21}$ observed at the maximum attenuation value, where the simulated $S_{21}$ resonance presents a slightly higher attenuation value (35.36dB) than the experimental one (33.45dB). The slightly higher value of $S_{11}$ as seen in Fig. 4.2 mainly comes from the calibration process. Imperfections may be caused due to the difference in the electrical size and therefore the diffraction properties of the calibrated sheet (metal) and the FSS sample. This leads to increased signal reception. Temperature, humidity, air gap
and misalignment are some of the factors not considered in the simulation, causing this slight difference.

![Figure 4.3](image.png)

**Figure 4.3.** Measured and simulated transmission spectra of the FSS ring array on 0.2 mm polycarbonate film for a normal incident plane wave over 2-18 GHz.

### 4.3.2 Polarization and Angular Sensitivity.

The circular ring elements have been reported to be less sensitive to incident angles when compared to many other simple shape elements such as crossed dipoles, tri poles etc. [2]. This was investigated for the thin polycarbonate FSS with circular rings. The two Floquet ports were set and the fields on either side of the circular rings were expanded as a set of Floquet modes exciting two orthogonal plane waves:

- one with electric field perpendicular (E⊥) to the plane of incidence of the screen, called TE polarization.
- other with electric field parallel (E∥) to the plane of incidence of the screen, called TM polarization as shown in Fig 4.1 (a).
A parameter sweep was carried out for the transmission response of the circular rings on 0.21 mm thick substrate for oblique incidence angles up to 90°.

**Figure 4.4.** Transmission response at oblique angles (0°, 30°, 60°, 90°) (a) TE polarization shows no change in stop band, resonating at 12.5 GHz (b) TM polarization shows a slight frequency drift as the angle of incidence increases.

The general features of the stop band remain the same as that for the normal incidence (0° incident angle) which shows a well-defined stop band at 12.5 GHz (see Fig. 4.3). From Fig. 4.4(a) for the TE mode, the higher order resonances (corresponding to higher angles of incidence) appear to remain at the resonant frequency. The change in stop band frequency is negligible, however broadening of the stop band is observed, especially for wide angle 90°. From Fig. 4.4(b), the TM mode appears to move slightly further from the resonant frequency. The resonant frequency shifts from 12.5 GHz to 13 GHz for higher angles from 30° to 90°, resulting in a frequency shift of 3.3%. As the angle of incident wave increases, for TM excitation, the rings appear flatter and the path for flow of current appears shorter, thereby causing the higher order shift in resonant frequency.
4.3.3 **Effect of change in substrate permittivity on resonance.**

The effect of the plastic substrate on the transmission characteristics for substrates with different permittivity were compared (see Fig 4.5). The FSS structure resonates at the highest frequency when air is the substrate material. As the permittivity of the substrate is increased, the stop band rejection frequency decreases. The resonant frequency reduced from 15 GHz (free standing FSS-no substrate) to 12.5 GHz using a polycarbonate ($\varepsilon_r=3.2$) backing of thickness 0.21 mm. A standard FR4 PCB backing substrate reduced the frequency to 11.84 GHz. Glass with similar thickness of 0.21 mm but with high relative permittivity $\varepsilon_r=10$ reduced the frequency to 9.3GHz.

![Figure 4.5](image-url)  
**Figure 4.5.** Plane wave transmission coefficient ($|S_{21}|$) for four different dielectric substrates.

The unprinted plastic substrate under normal incident plane wave transmission was studied. When the substrate thickness becomes a significant part of a wavelength at the frequencies of interest, the reflection between the air and plastic interfaces creates a cyclic filter effect due to the standing waves generated in the plastic substrate. Fig 4. 6 shows this
effect for a change in substrate thickness ranging from 1 mm to 12 mm with step size of 4 mm. As the substrate thickness increases, the $S_{21}$ value varies more rapidly versus frequency.

![Graph showing the effect of substrate thickness on $S_{21}$](image)

**Figure 4.6.** Plane wave transmission coefficient ($S_{21}$) for an un-printed polycarbonate substrate, $\varepsilon_r=3.2$ for different thicknesses.

### 4.3.4 Effect of change in substrate thickness on resonance and bandwidth.

The FSS structure and the thickness of the substrate, up to certain values, demonstrates the stop band frequency variation of the FSS structure. The bandwidth of the band gap can be adjusted by varying the thickness of the plastic substrate (see Fig 4.7).
Figure 4.7. Effect of plastic substrate thickness on the stop band frequency and the 10 dB bandwidth for \( \varepsilon_r = 3.2 \).

Fig. 4.7 shows the reduction in the stop-band frequency with an increase in substrate thickness. For thin substrates around 0.2 mm the stop band centre frequency changes rapidly as the thickness increases. As a result, it is possible to obtain significant frequency reduction by using thin polycarbonate sheet as the supporting dielectric substrate. There is also little advantage in using polycarbonate sheets thicker than 1.8 mm. Thicker sheets give greater structural integrity but thinner sheets are flexible so can be used as conformal coatings with greater optical transparency. Fig 4.7 shows the dependence of the -10 dB bandwidth on substrate thickness ranging from 0 to 12 mm. The bandwidth was predicted to decrease as the resonating frequency decreases [7], but the use of the thin plastic substrate reverses the effect at certain wavelengths and the thickness controls the bandwidth of the structure. The peaks in the bandwidth curve in Fig. 4.7 result from the
combined dielectric loading effect due to the thickness of the plastic and the back reflections from the plastic for a given substrate thickness. The transmitted and the reflected signal within the plastic arrive at the metal rings with varying phase depending on the frequency. This means that as the frequency is varied, the impedance at the frequency selective surface changes. This analysis shows the impedance at the FSS screen over the frequency range of 2-18 GHz with constant thickness of plastic. The broadening and narrowing of the frequency curve is evident near the quarter and half wavelength thicknesses of plastic substrate. There is a tuning effect in which dielectric thickness can be used to control both the resonant frequency and the bandwidth of the band gap. Adjusting both the ring diameter, the separation and the substrate thickness allows the design of an FSS structure with the desired resonant frequency and bandwidth.

The FSS design (Fig 4.1) is reflective in Ku band at 12.5 GHz and transparent at other frequencies. Further work was done on more complex single layer designs to lower frequencies while retaining the small unit cell size. The detailed discussion is in the following sections.

4.4 MINIATURIZATION OF FREQUENCY SELECTIVE SURFACES

Recently there has been developing interest in the application of frequency selective surfaces to building windows [8-10] and inner walls of buildings [11]. However, their use at cellular frequencies like 2.2 GHz or less means array elements need to be physically large (nearly one-half wavelength) in order for them to resonate. The large element size or lattice periodicity leads to practical difficulties, especially on curved surfaces [12]. The problem of the large size of a unit cell can be addressed by modifying the resonant element, which in turn modifies the transmission response of the surface. The term convoluted was first used in [13], where the geometry of a simple dipole was transformed into meanders;
thereby miniaturizing the element while keeping the unit cell size the same. The unit cell with complex element shapes like twists, meanders, interweaves and peaks are all considered as convoluted shapes. Convoluting the element fills the space within the loop or outside the centered type FSS by additional lengths of conductor. The two major advantages of miniaturizing the FSS elements are:

- Significantly reduces the cell size area with enhanced bandwidth [14].
- Improves the angular stability of the frequency selective surface [12].

The concept of convoluting a conductor led to the design of the Hilbert curve [15], which offers the space filling properties by being able to fit a long wire into a small space. There are simple mathematical calculations available for convoluting the structure, which are used for designing frequency selective surfaces [13], compact antennas [16] and high impedance surfaces [17].

4.5 MINIATURIZED FREQUENCY SELECTIVE SURFACE MODELING

4.5.1 Design Approach

The square loop FSS was considered as a basic design model because it offers higher inter cell capacitance and better performance in terms of angular stability, polarization and band width [18]. An exhaustive study explored possible unit cell element configurations while miniaturizing the FSS square element. Meander lines were introduced to fill the available space in the square. The physical factors like the conductor length, track width, separation and possible number of meanders need to be considered while convoluting the structure. In this study, we chose the half-length ($L_1/2$) of one arm of the square element (i.e. 6.1mm) and convoluted it with the maximum possible number of meander peaks as shown in Fig 4.8.
The other side of the unit cell was designed by reverse mirror imaging, forming three outward and three inward meander peaks on each arm of the original square element. The meanders have a peak angle of 20° and are 3 mm deep. These triangular peaks help to increase the inter cell capacitance and the inductance in the cell by interweaving of neighboring elements without affecting the periodicity of the unit cell. This increase in the electrical length of the basic square loop leads to a larger equivalent cell size without changing the physical unit cell size.

4.5.2 FSS physical specifications

Fig. 4.9(a) shows the square loop unit cell and Fig. 4.9(b) shows the miniaturized meandered square loop. The miniaturized square loop FSS was printed on a thin polycarbonate sheet (εr=3.2, tanδ=0.0025, thickness of 0.21 mm). The FSS was designed with the aid of CST Microwave Studio software using the frequency domain solver and the unit cell boundary conditions in x and y directions.
Figure 4.9 (a) Original Square loop (b) Convoluted square loop with six meander peaks on each arm element of square loop.

The printed silver has a conductivity, \( \sigma = 4.3 \times 10^6 \) S/m. While the ink is opaque, optical transparency was ensured by keeping the track width less than 0.2 mm. A finer mesh stencil with 100T (T-threads) was used in screen printing these small track widths. The periodicity of the FSS was 12 mm in both horizontal and vertical directions. The detailed dimensions of the fabricated FSS are given in Table 4.2.

**Table 4.2 Physical dimensions of the designed miniaturized FSS element.**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Description</th>
<th>Dimensions (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( L_1 )</td>
<td>Element size</td>
<td>12</td>
</tr>
<tr>
<td>( L_2 )</td>
<td>Outer peak to outer peak</td>
<td>18</td>
</tr>
<tr>
<td>( L_3 )</td>
<td>Outer peak to Inner peak</td>
<td>12</td>
</tr>
<tr>
<td>( L_4 )</td>
<td>Peak length</td>
<td>3</td>
</tr>
<tr>
<td>( t_1 )</td>
<td>Peak thickness</td>
<td>1.125</td>
</tr>
<tr>
<td>( t_2 )</td>
<td>Track width</td>
<td>0.75</td>
</tr>
<tr>
<td>( p )</td>
<td>Unit cell size</td>
<td>16</td>
</tr>
</tbody>
</table>
In modelling the structure, it was assumed that the proposed FSS is an infinite periodic structure, with the repetition of conducting elements along the $x$ and $y$ axes. These unit cells were arranged in a square grid lattice with the periodicity $p$ maintaining the spacing between the peaks. Therefore, a densely packed array in the $xy$ plane was obtained as shown in Fig 4.10. The small spacing between the conduction elements ensures a stable frequency response for oblique angles [19].

![Figure 4.10 Array of closely packed meander line FSS unit cells arranged in $xy$ plane.](image)

4.6 EFFECT OF MINIATURIZATION.

4.6.1 Effect of meanders on stop band frequency.

The original square loop resonates at 5.65 GHz with a modelled -10 dB bandwidth of 2.6 GHz and the transmission loss of 40 dB, as shown in Fig 4.11. The modified structure resonates at 2.36 GHz with transmission loss of 2 dB less than that of the square loop. However, this FSS structure has a stop bandwidth of 1 GHz, which implies that with
the decrease in resonating frequency, the obtained bandwidth has decreased by more than 60%.

![Figure 4.11](image_url)

**Figure 4.11** Comparison of simulated $S_{21}$ for a square loop and the meandered square loop of same unit cell size excited by a plane wave at normal incidence.

### 4.6.2 Effect of number of meanders on stop band frequency.

The influence of the number of meanders on the notch frequency and the bandwidth of the structure is shown in Fig. 4.12. The analysis was done for up to six meanders on each arm of a square with the peak height of each meander of $L_d = 3$ mm. This maximum number was determined by the printing tolerances for minimum acceptable resolution. The resonant wavelength, $\lambda_r$, continues to increase with the increase in the number of meanders, but the stop-band width around the resonant frequency decreases up to 44% compared to the simple square loop.
Figure 4.12 Variation of resonant frequency, \( f_r \) and the transmission bandwidth as the number of meander peaks in the convoluted square loop was increased.

4.6.3 Effect of unit cell size on stop bandwidth.

In order to avoid the grating lobes, the unit cell size (\( p \)) was kept small following the grating lobe relation given in equation (4.5). In the meandered line FSS, the unit cell size is less than a wavelength at normal incidence (0°) and half of the wavelength for oblique angles (such as 45°). The larger unit cell size lead to the presence of grating lobes, which are more significant on curved surfaces. A theoretical analysis showed the effect of unit cell on the bandwidth (see Fig 4.13). For FSS elements with no interweaving (>15 mm in this case) the resonant frequency slowly increases and the stop band gets smaller as the elements get more distant from each other. On the contrary, small unit cell size is required to keep the equivalent capacitance between the meanders high, which reduces the resonant frequency and increases the bandwidth.
Figure 4.13 Variation of resonant frequency, \( f_r \) and the transmission bandwidth as the unit cell size of the convoluted square loop changes.

4.6.4 Frequency reduction due to meanders.

By convoluting each side of the square element, the frequency of the unit cell reduces significantly. The original square loop resonating at 5.65 GHz has a side dimension of 12 mm and the area is 144 mm\(^2\). The meander square however, resonates at 2.2 GHz. The analysis showed that for a square loop to resonate at 2.2 GHz, the side length needs to be 33 mm. Therefore, 61.6% frequency reduction is achieved by modifying the structure, as calculated by:

\[
\text{Frequency Reduction} = \frac{\text{Square freq.} - \text{Meandered square freq.}}{\text{Square freq.}} \times 100\% \quad (4.7)
\]

4.7 MEASUREMENTS OF MINIATURISED FSS

After optimizing the meandered line FSS, the final design was fabricated using screen printing on a thin polycarbonate sheet 280 mm \( \times \) 260 mm (see Fig.
The frequency response was measured for normal and off-normal angles of incidence. Two standard gain horn antennas were used for transmission and reception. The antennas were connected to a vector network analyzer, which was used to sweep the frequency between 2 and 8 GHz. The FSS screen was illuminated from the far field (60cm) from each antenna. The measurement set-up is similar to the one described in Chapter 3.

**Figure 4.14** A photograph of the thin meandered stop-band FSS. The dotted line shows the square grid array arrangement of the FSS elements.

### 4.7.1 Plane wave normal incidence response

Using the full-wave simulation, the physical parameters of the meandered square loop were fine-tuned to achieve the final design. A strong resonant frequency design is clearly observed at 2.32 GHz. Fig 4.15 presents a comparison between the simulated and measured transmission characteristics of the meandered square loop at normal incidence. The measurement results are in good agreement with the simulated results, which validates the fabrication process. Due to the frequency range limitation of horns used for measurements, the response below 2 GHz is not included in the results. However, the transmission loss observed in the simulated results is 10 dB less than that obtained from
measurements. Factors like temperature, humidity, air gap, foreground reflections, misalignment in set-up and the finite nature of actual screen were not considered in the computer simulations, and may account for the difference in attenuation. In addition, the conductivity of the dry ink is approximated which can affect the attenuation of the structure.

![Graph](image)

**Figure 4.15** Comparison between the measured and simulated transmission response through the meandered square loop at normal incidence ($0^\circ$).

In order to check the impact of different angles of incidence on the resonant frequency of the FSS, simulations and measurements were considered at off-normal angles.

### 4.7.2 Plane wave off normal incidence

It is known as the angle of incidence of the plane wave changes, the transmission and the reflection characteristics change [20]. Therefore, it was important to design an FSS structure with the lowest possible angular and polarization sensitivity. Fig. 4.16 shows the simulation and measured results of the transmission for perpendicular (TE) polarizations,
for four angles of incidence $0^\circ$, $30^\circ$, $45^\circ$, $60^\circ$ respectively. Fig. 4.16(a) shows $S_{21}$ for all the four angles. The stop-band is centred at 2.32 GHz. However, the transmission loss does vary and increases as the angle of incidence increases.

Figure 4.16 Off normal TE polarization transmission response for meandered square loop. (a) Simulation results (b) Measured results.

Fig 4.16(b) shows the measured response of FSS for TE polarization at oblique angles. The centre frequency shows slight drift ($< 6.5\%$) from the resonant frequency at normal incidence. The average transmission loss of 28 dB, 23 dB, 22 dB and 18 dB can be observed over the useful frequency band for $0^\circ$, $30^\circ$, $45^\circ$ and $60^\circ$ respectively. It should also be noted that the TE bandwidth for both the measured and simulated FSS increases with an increase in angle of incidence.

Fig 4.17 shows the simulated and experimental results of the transmission response through the FSS for parallel (TM) polarizations for four angles of incidence $0^\circ$, $30^\circ$, $45^\circ$ and $60^\circ$ respectively. The simulations show a well-defined resonant frequency at 2.32 GHz with slightly varying transmission losses as the angle of incidence increases as shown in
Fig 4.17(a). However, the stop-band width gets narrower as the angle of incidence increases. The Fig 4.17(b) shows the measured results. For smaller angles like 30° and 45° the resonances are close to the resonant frequency of the FSS structure at normal incidence. However, for higher angles like 60°, the resonant frequency starts to drift away from resonant frequency by 23%. The difference in the measured and simulated response for larger angles can be contributed by factors such as the target size seem to decrease as the angle of incidence increases in measurements which does not happen in simulation sweep, silver paste ink conductivity is approximated, experimental errors due to the measurement set up and also the edge diffractions occurring at larger angles when the measured sample has large edge ratio as compared to the simulation sweep. Therefore, major design improvements are required to achieve the angular stability at higher angles of incidence.

![Graph](image)

**Figure 4.17** Off normal TM polarization transmission response for a meandered square loop. (a) Simulation results (b) Measured results.

### 4.8 FSS ON CLEAR GLASS.

The existing research and the available literature reports that when an FSS is printed on a dielectric medium, the free space frequency will change [21]. Therefore, for potential
shielding application of FSS on windows, the interaction of glass and FSS need to be examined. The frequency selective surface on glass is treated as a transmission line with a characteristic impedance, and the length of the line is dependent on the substrate thickness. In this analysis, a standard loss free glass with relative permittivity of $\varepsilon_r = 4.8$ and thickness 5 mm was considered. The simulated transmission performance of the standard glass without FSS is shown in Fig 4.18(a). When the FSS is printed on the glass, it can block the transmission at a specific frequency or at various frequencies depending on the type of FSS.

As shown in Fig. 4.18(b), the presence of the FSS modifies the transmission response of the overall structure. This composite structure blocks the transmission of radiation at 1.89 GHz, acting as a good reflector for that specific frequency. With this response, the FSS can find potential applications in shielding the windows and walls of buildings and offices shielding the internal wireless communications. Factors like

![Figure 4.18](image-url)
manufacturing cost, installation and maintenance requirements need to be investigated further. The frequency can be tuned to different bands by scaling the FSS element design.

The design goal can be further extended from a thin flexible single layer FSS to a multi-layer FSS to achieve dual stop bands, broader stop bands and high angular stability. These issues are discussed in following chapters.

4.9 SUMMARY

In this chapter, a novel 2D frequency selective surface comprising of circular rings was screen printed on thin (0.21 mm), flexible transparent plastic substrate (relative permittivity 3.2). It was designed, fabricated and tested in the frequency range 10-20 GHz. The plane wave transmission and reflection coefficients agree with the numerical modelling of the FSS structure. The effective permittivity and thickness of the backing sheet has a significant effect on the frequency characteristics of the FSS. The stop band frequency was reduced from 15 GHz (no backing) to 12.5 GHz with 0.20 mm thick polycarbonate backing. The plastic substrate thickness beyond 1.8 mm thickness has minimal effect on the resonant frequency. While the inter element spacing controls the stop-band frequency, the substrate thickness controls the bandwidth. Much of this work was published in [22]. The study was extended further to a single layer convoluted frequency selective surface in the form of a meandered square loop with stop band characteristics in the s-band was modelled and fabricated for electromagnetic shielding. The square loop unit cell size needed at a specific frequency (2.32 GHz) was reduced significantly by convoluting the square loop element. Each arm of the square loop was replaced by six meandered peaks, filling the available space and thereby increasing the resonant element length. The frequency reduction of about 61.6% is achieved by modifying the structure. The geometry of this structure provides the flexibility of increasing the bandwidth by adjusting the interweaving between the peaks and also lowering the frequency by managing the number of peaks. However, the number of peaks possible on each side of the square loop depends on the length of meander peaks, the unit cell size and the
available printing resolution. The analysis showed for lower periodicities (10 mm) the stop band width was 74% wider than the larger periodicities. The thin flexible prototype was fabricated with a high resolution miniaturized FSS using the screen printing technique. The transmission response for normal and off-normal angles were in good agreement. Since this FSS was designed for the potential shielding application of radio secure environments in buildings, a simplistic approach was used to see the effect on the propagation of signals through the glass with and without the FSS. However, additional analysis is required to improve the propagation and installation cost of big screens.
4.10 REFERENCES


CHAPTER 5

MULTI LAYER FREQUENCY SELECTIVE SURFACE

5.1 INTRODUCTION

This chapter presents the double-sided FSS with a structure comprising two square element arrays printed on each side of a thin flexible substrate. The structure blocks the transmission at 7.6 GHz and provides a -10dB stop bandwidth of 8.12 GHz. A number of offset techniques were explored to improve the bandwidth of the double-sided FSS without changing the unit cell size ($\lambda_0/5$). Many analytical and numerical techniques have been used for designing multi-layer FSS in the past. The element lattice arrangement in single and double layer FSS [1], different element – dielectric geometries [2] and FSS integrated with antennas [3] have been used to increase the bandwidth. However, the use of thick substrates and stacked multi-layers make the structure thicker, less mechanically flexible and less transparent. Fractals [4] and other complex structures with different specifications such as magnetic absorbers [5], space filling curves [6], and high impedance surfaces [7] have been used to improve the bandwidth. In all these cases, the filtering capacity was improved but the shielding bandwidth was narrow. The driving force for investigating a double sided FSS was to:

- less complex structure for double layer FSS
- lower the resonant stop band frequency of the overall structure
- provide an ultra-wide band FSS
- achieve stability over wide angles of incidence and different polarizations
- retain the optical transparency/translucency of structure even in double sided FSS
- use a thin and mechanically flexible substrate to make it applicable for shielding windows and conformal surfaces.

Extending the concept of double sided FSS, the latter half of this chapter presents a miniaturized dual layer FSS screen printed on each side of a thin flexible dielectric substrate. The FSS exhibits -10dB stop bandwidth of 2.27 GHz ranging from 1.066 to 3.34 GHz. The objective of this work was to design a thin FSS based wall configuration which can provide frequency shielding at GSM bands (e.g. DS1800 used for mobile communications). The analysis involves meandering the square loop at four corners and then offsetting one of the layers to provide maximum coupling between the resonant elements. These techniques have proven to help in reducing the notch frequency of the structure. The dimensions of the FSS elements are much smaller ($\lambda_o/22$) than the free space operational wavelength, $\lambda_o$. The effect of meandering the FSS element on the overall performance and the various offset techniques used to enhance the bandwidth are presented in this chapter. Finally the screen printed prototype was fabricated and measured. For both single and double-sided FSS, the measured and simulated results are in good agreement. The features of the structure include the flexible nature, compact unit cell size, stable frequency and polarisation response over the wide variation of angle incidence. The screen printing technology has made it possible to cheaply manufacture frequency selective shields for room walls and windows which can allow/block the transmission of specific frequency bands.
5.2 DOUBLE SIDED FREQUENCY SELECTIVE SURFACE

Compared to the simple single sided ring FSS with a notch at 12.5 GHz discussed in Chapter 4, there is need to reduce the resonant frequency to much lower frequencies for civil applications. In order to reduce the stop band notch of an FSS, the capacitance and the inductance due to the resonant elements of the structure needs to be increased (eq 4.4). Apart from convoluting the element in order to reduce the resonant frequency of the FSS which was discussed in latter half of chapter 4, the other way to do it is to print the FSS on both sides of the substrate. A single square unit cell is printed on one side of a thin polycarbonate substrate and an identical cell is printed in an alignment on the other side. The surface behavior of the double sided FSS depends on the mutual interaction between the adjacent elements and the interaction with elements on the either side of the substrate. The direction of current in the top unit cell is opposite to the direction in the bottom unit cell, thus cancelling each other producing the resonance. By choosing the proper alignment of these unit cells, not only the desired stop band characteristics, but also a broad bandwidth can be achieved for a double-sided FSS.

5.2.1 Physics: FSS Design and specifications.

The FSS structure consists of printed metallic layers on both sides of the dielectric substrate. The pattern (Fig. 5.1) was a regular array of square loops and the supporting dielectric substrate was polycarbonate, with relative permittivity, $\varepsilon_r = 3.2$, loss tangent 0.0025 and thickness, $h = 0.21$ mm. Fig. 5.1 shows the layout and the respective cross section of the basic design. The top and the bottom unit cells are aligned. The interaction of the two layers of FSS influences the operational mechanism of the structures as the thin substrate ensures the conductors are highly coupled.
Figure 5.1. Double sided Square Loop Stop band FSS unit cell. (a) FSS- Top side. (b) FSS- Bottom side. (c) Equivalent circuit showing inductance and capacitance associated with the double sided square loop. (d) Cross-sectional side view from x-z plane showing the conductors are aligned in both the x and y directions.

In the modelling investigation of the FSS structure, it was assumed to be an infinite periodic structure. The FSS was illuminated by a plane wave, with an electric field vector $\mathbf{E}$ oriented in the $y$ direction and the magnetic field vector $\mathbf{H}$ oriented in the $x$ direction.

The single layer FSS structure behaves like a series LC resonator where the loop contributes to inductance and the gap in between the two adjacent elements provides capacitance [8]. At resonance, the equivalent impedance of the structure is at its minimum value, thus blocking the transmission and making it a near-perfect reflector [9]. The behavior of the multi-layer FSS also depends on the interaction between the square loops on the two layers. The two FSS layers were separated by a thin dielectric substrate represented as a short transmission line whose length is the electrical thickness of the substrate [10]. Therefore, the equivalent circuit was simplified as a parallel circuit comprising the top series LC resonator (FSS1) and bottom series LC resonator (FSS2) (see Fig.5.1). The characteristic impedance of the substrate is $Z_l = Z_0 \sqrt{\varepsilon_r}$, where $\varepsilon_r$ is the dielectric constant of the substrate, $l$ is the length (equal to thickness of the substrate) and the free space
impedance $Z_o = 377 \Omega$. The current on the square loop on one side of the FSS structure produces a magnetic field around it that couples with the elements on the opposite side. This inductive coupling becomes stronger with decrease in the substrate thickness. Capacitive junctions are formed at the locations where tracks on opposite sides of the FSS structure overlap. The mutual coupling between the two sides was modelled as mutual inductance and capacitance. The values of mutual capacitance, $M_c$, and mutual inductance, $M_l$ depend on the overlap of the metallic tracks and vary in different configurations. The transmission is blocked by this FSS structure at its resonant frequency, therefore behaving as a stop band filter. The performance of the FSS was calculated using CST Microwave Studio, and the unit cell boundary conditions were set in the directions of periodicity.

### 5.2.2 Layer Offset Technique

The enhancement of bandwidth was achieved by lateral displacement of the bottom side relative to the top. The relative lateral displacement is important in the electromagnetic design as it involves a change in the mutual inductance and capacitance of the conducting elements. Various offset techniques were used to implement shifts in the stopband frequency while maintaining the compactness of the unit cell. In the numerical model, the top side was fixed and the bottom was shifted in $x$ and $y$ directions independently, as shown in Fig. 5.2 and 5.3.
**Figure 5.2.** Double sided square loop stop band FSS unit cell with half period displacement in $x$ or $y$ axis.

(a) FSS top side. (b) FSS bottom side.- displaced in x-direction. (c) FSS bottom side.- displaced in y-direction. (d) Cross sectional view from x-z plane, $\delta_x = 0.5L_1$. (e) Cross sectional side view from y-z plane, $\delta_y = 0.5L_1$.

Shifting the square loop on the bottom side of the dielectric by a half-cell in $x$-axis ($\delta_x = 0.5L_1$) or in $y$-axis ($\delta_y = 0.5L_1$) did not affect the centre frequency of the stop band. However, the displacement parallel to incident E field ($y$) resulted in a slightly broader bandwidth as compared to the displacement parallel to the magnetic field ($x$). Next, a half-period offset was made in both $x$ and $y$ axes simultaneously, i.e. $\delta_x = \delta_y = 0.5L_1$, as shown in Fig.5.3. Such an offset showed a wider bandwidth due to the increase in mutual inductance, $M_l$ and the mutual capacitance, $M_c$ as compared to the other FSS configurations. The lumped inductor and capacitor are now arranged in a way that they can have maximum coupling to the electric and magnetic fields of the incident plane wave.
Figure 5.3. Double sided square loop stop band FSS unit cell with half period displacement in $x$ and $y$ axis.

(a) FSS top side. (b) FSS bottom side displaced in $x$ and $y$ direction (d) Cross sectional side view from y-z plane, $\delta_x = 0.5L_1$ and $\delta_y = 0.5L_1$. The dimensions of the structure used in this investigation are given in the Table 5.1.

Table 5.1. Physical dimensions of FSS square loop (see Fig. 5.2 and 5.3)

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Description</th>
<th>Dimensions(mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_1$</td>
<td>Unit cell size</td>
<td>8.00</td>
</tr>
<tr>
<td>$L_2$</td>
<td>Track length, y axis</td>
<td>7.20</td>
</tr>
<tr>
<td>$L_3$</td>
<td>Track length, x axis</td>
<td>7.20</td>
</tr>
<tr>
<td>$t$</td>
<td>Thickness of track</td>
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</tr>
<tr>
<td>$s$</td>
<td>Spacing in between loops</td>
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</tr>
<tr>
<td>$w$</td>
<td>Width of element</td>
<td>0.30</td>
</tr>
<tr>
<td>$h$</td>
<td>Thickness of substrate</td>
<td>0.21</td>
</tr>
</tbody>
</table>

5.3 PLANE WAVE PERFORMANCE

5.3.1 Transmission response at Normal Incidence

The simulation results of the transmission $S_{21}$ and reflection $S_{11}$ characteristics of the double sided FSS with no offset and with half-cell offset for normal incidence are shown in Fig 5.4. The analysis was done using CST Microwave Studio. As the FSS element was
displaced on bottom side, opposite currents flowing in the loop tracks increase the mutual inductance and capacitance of the structure, thereby shifting the stop band. The $S_{21}$ plots show that the frequency decreases from 9.14 GHz to 7.6 GHz with the offset in the bottom layer. However, the peak transmission loss observed in the double sided square loop without offset is nearly 20 dB less than the square loop with offset.

![Figure 5.4](image)

**Figure 5.4.** Transmission and reflection response of double sided square loop FSS for normal incidence. The red line (---) and green line (solid) represent the transmission and reflection response for the displacement of $\delta_x = \delta_y = 0$.

The displacement also increases the bandwidth of the FSS. The simulated results show that the maximum bandwidth was obtained by positioning the FSS such that the individual element sides of a bottom side lie at one half-cell apart in $x$ and $y$ direction to those of the top side when viewed from the normal angle of incidence. The results are given in Table 5.2.
Table 5.2: Transmission response of the double sided FSS with various configurations at normal wave incidence.

<table>
<thead>
<tr>
<th>Substrate thickness, h</th>
<th>Displacement</th>
<th>$f_r$(GHz)</th>
<th>-10dB BW(GHz)</th>
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<tr>
<td></td>
<td>$\delta_x$</td>
<td>$\delta_y$</td>
<td></td>
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<tr>
<td>0.2mm</td>
<td>0</td>
<td>0</td>
<td>9.14</td>
</tr>
<tr>
<td>0.2mm</td>
<td>0.5$L_1$</td>
<td>0</td>
<td>14.18</td>
</tr>
<tr>
<td>0.2mm</td>
<td>0</td>
<td>0.5$L_1$</td>
<td>14.18</td>
</tr>
<tr>
<td>0.2mm</td>
<td>0.5$L_1$</td>
<td>0.5$L_1$</td>
<td>7.60</td>
</tr>
</tbody>
</table>

The efficiency of the double-sided FSS in terms of reflection ($S_{11}$) and transmission coefficient ($S_{21}$) was calculated using the equation as given below [11]:

$$\eta = \sqrt{|S_{11}|^2 + |S_{21}|^2}$$  \hspace{1cm} (5.1)

For a lossy structure, $0 < \eta < 1$ which is the case for square FSS with offset and no offset over the frequency range of 2-18 GHz (see Fig 5.5). However, it should be noted the efficiency starts to decrease in case of half-cell displacement as the frequency starts to increase.

![Figure 5.5](image_url)

**Figure 5.5** Efficiency ($\eta$) in terms of reflection and transmission coefficient for the zero offset and half-cell offset FSS shown in Fig 5.1 and Fig.5.3 respectively.
5.3.2 Polarization and wide angle of incidence effects:

At an angle other than normal incidence, the plane wave is described as a superposition of two orthogonally polarized waves: one wave with perpendicular electric field TE (transverse electric) polarization and other with parallel electric field called TM (transverse magnetic) polarization with respect to the plane of incidence [12]. In order to check the impact of incident angle, various incident angles (0°, 15°, 30°, 45°, 60°) were investigated for TE and TM polarizations. It is evident from Fig.5.6, an identical response for both TE and TM modes of polarization at normal incidence, θᵢ = 0° is achieved.
Figure 5.6. Transmission coefficients as a function of frequency for various incident angles for double offset double sided FSS. (a) TE perpendicular polarization shows frequency shift of 2% over angles 0° to 60° (b) TM parallel polarization shows frequency shift, of nearly 10% over angles 0° to 60°.

The general features of the stop band remain the same as that of the normal incidence for TE polarization. The double sided square loop FSS has a very small (less than 2%) change in resonant frequency for TE polarization compared to the TM polarization response. Fig. 5.6(a) shows a well-defined stop-band at 7.60 GHz and the higher order resonances corresponding to higher angles (θ > 40°) appears unchanged. Fig. 5.6(b) shows the TM mode shifts by 6% (7.60 GHz to 7.15 GHz) within the 30° angle of incidence. For TM polarization, at higher angles of incidence (θ > 40°), the first grating lobe exists at 9.6 GHz for 45° and the other grating lobe exists at 9.4 GHz for 60° shifting the resonant frequency further from resonant frequency, f_r (see Fig. 5.7). This confirms that for higher angle of incidence, the FSS shows angular sensitivity for TM polarization.
Figure 5.7. The resonant frequency variation for a double offset FSS as a function of angle of incidence for TE and TM polarization. The grating lobes start to appear for angles greater than 40° for the TM polarization case.

5.4 Bandwidth Control.

The parametric study of the double-sided square element FSS can help to select proper dimensions and alignments for widening or narrowing the bandwidth. The spectral response was plotted by varying various physical parameters in the design, including the dielectric substrate thickness, \( h \), the element width, \( w \) and the space between the adjacent elements, \( s \).

5.4.1 Influence of dielectric thickness:

The fundamental resonant frequency of the FSS is altered by changing the thickness of the supporting dielectric. With the increase in the thickness of the dielectric, the layer offset configurations show an initial decline of the resonant frequency from the free space value. At the boundary, the low order evanescent Floquet modes decay exponentially...
with distance from the conducting elements. This modifies the relative amplitudes and the resonant frequency of the FSS with respect to the supporting dielectric layer [13].

![Graph showing the -10dB S21 bandwidth of the fundamental resonance of double sided (DS) FSS with substrate offset in x direction and double offset in x and y directions for substrate thickness (h) ranging from 0-20 mm.]

**Figure 5.8** The -10dB S21 bandwidth of the fundamental resonance of double sided (DS) FSS with substrate offset in x direction and double offset in x and y directions for substrate thickness (h) ranging from 0-20 mm.

For half period displacement in either x or y directions, the structure resonates at a higher frequency of about 14.18 GHz with a bandwidth of nearly 9 GHz for 0.21 mm dielectric thickness. For the same thickness and half period displacement in the x and y directions, the structure resonates at a slightly lower frequency of 7.60 GHz with a bandwidth of nearly 8.20 GHz (see Fig. 5.8). This means that the half-cell displacement increases the mutual inductance, $M_l$ and slightly increases the mutual capacitance, $M_c$ (Fig. 5.1c) which lowers the band stop frequency. Beyond the thickness of 2 mm, there was a periodic oscillation and rise in bandwidth. The peaks in the S21 bandwidth curve in Fig 5.8 were due to the combined effect of dielectric loading on two sides of the plastic and the back reflections from the plastic for a given substrate thickness.
5.4.2 Influence of inter element spacing:

As the inter element spacing was increased, the mutual coupling decreases and this leads to grating lobes in the transmission curve which reduces the angular stability of the response. The mutual element coupling was unaffected by the change in the angle of incidence. Only the phase associated with the induced currents in the FSS elements change with angle of incidence [14].

![Figure 5.9. Simulated transmission response for the double sided square loop FSS with x and y offset bottom side, for different values of spacing, s. Physical dimensions given in Table 5.1 were considered for analysis.](image)

The square lattice elements were placed following the general formula given in [15]. For normal incidence, $L_y/\lambda_0$ is less than 1. The plot in Fig. 5.9 shows that if the spacing was decreased to 0.2 mm without changing the other parameters, the bandwidth was further enhanced by 2.3%. However, the printing tolerances will limit the practical FSS structures. No grating lobes appear up to an inter element spacing of 2 mm.
5.4.3 Influence of element width

Another geometrical parameter found to regulate the bandwidth of the FSS was the element width, $w$ of the square loop (Fig. 5.10) where the inner circumference of the square loop changes and all other parameters were unchanged. This is because the circumference for the flow of current is reduced as the track width increases which lowers the inductance and the notch frequency, $f_r$, shifts higher.

![Figure 5.10](image)

**Figure 5.10.** Simulated transmission response for the double sided square loop FSS with $x$ and $y$ offset bottom side, for different values of track width $w$. As the loop size decreases the inductance increases, narrowing the bandwidth seen for a track width of 0.1 mm the bandwidth is 6.61 GHz.

5.5 MULTILAYER MINIATURIZED ELEMENT FREQUENCY SELECTIVE SURFACES

For FSS applications at low frequency where small screens of relatively small electrical dimensions are desirable, the unit cell size needs to be minimized without compromising the angular stability [16]. To address this problem, resonant lengths can be meandered and packed into the smaller unit cell. The concept of meandering the array
element not only reduces the notch frequency but also ensures a stable stop band (in case of loop type FSS) responses over the oblique angles of incidence and isolates the fundamental resonance from the grating lobes [17]. In a traditional single-layer FSS, tight tolerance conditions are required unless the unit cell element dimensions are a small fraction of the operating wavelength, as is the case for the novel convoluted elements in [17]. Single-layer band pass spiral FSS structures with miniaturized unit cell of $0.058\lambda_o$ [18] and $0.061\lambda_o$ in dimensions, were developed in [19]. The miniaturized characteristics were stable with respect to the different polarizations and incident angles. The only drawback associated with these FSS structures was the use of thick substrate.

The approach of miniaturizing the unit cell was extended in designing double sided FSS. The miniaturized element comprised of a metallic loop and a wire grid printed on either side of Duroid substrate, with a unit cell size of $0.083\lambda_o$. The meandered tracks in a unit cell act as lumped inductive and capacitive elements which can be placed in order to couple the magnetic and electric fields of an incident plane wave, respectively to achieve band-pass behavior, as shown in [20]. A new miniaturized double sided FSS comprising of micro-wire resonating elements with unit cell size $0.067\lambda_o$ was also presented in [21]. The structure demonstrates a better stability over wide angles of incidence and different polarizations. However, in these studies, the FR4 or Roger RT/Duroid was selected as substrate, which is not mechanically flexible. Such structures are not useful for shielding applications which involve conformal surfaces. In order to overcome this limitation, multilayers of FSS are cascaded with quarter wavelength spacing between the layers. This makes the structure thick and bulky, and the angular sensitivity of the FSS is increased.
5.5.1 Physics: Element of Design

The FSS consists of two screen-printed inductive layers on a thin flexible dielectric substrate. The square loop element was chosen as the basic model to build the final FSS structure because of its good performance in the microwave frequency spectrum [22]. The final meandered double sided FSS design is based on the basic square loop structure, as shown in Fig. 5.1. The physical dimensions of the final structure one same as tabulated in Table 5.1 and the operational mechanism is as described in Section 5.2.1 respectively. The coupling coefficient between the two layers controls the centre frequency and bandwidth of the FSS structure [23]. The unit cell boundary conditions were set in the directions of periodicity and the fields were expanded as a set of Floquet modes.

5.5.2 Design using Meandered Square

The structure was optimised manually to reduce the resonant frequency. The conducting element of the basic square model was meandered at the four corners in two stages, as shown in Fig 5.11. Meandering reduces the electrical size of the FSS and can greatly improve the overall filtering performance of FSS.

![Figure 5.11](image)

**Figure 5.11.** Stages of meandering showing the top layer only (a) Basic Square loop (b) 1st convoluted stage with meanders n=4 (c) 2nd convoluted stage with meanders n=12.
The meandering was done in a way that it fills the space of the square loop generating the maximum possible resonantantor. This new approach of space filling meanders increases the equivalent inductance and the gap between the proximal elements increases the capacitive coupling.

5.5.2.1 Transmission response of meandered stages

As the number of meanders was increased from no meanders (i.e. the basic square loop) to 12 meanders (2nd convoluted stage), the centre frequency of the stop band decreased from 8.7 GHz to 5.4 GHz. The -10dB stop bandwidth shows a drop from 30.7% to 20%. Fig 5.12 compares the transmission coefficients with that from a single-sided FSS.

![Figure 5.12](image)

**Figure 5.12.** Effect on insertion loss and stop band frequency of a single layer FSS caused by meandering the FSS element. The resonant frequency shift shows the percentage decrease relative to the basic square model.

The bandwidth of the FSS can be controlled by increasing the number of meanders \(n\) in the element, as seen Table 5.3. The single sided structure (see Fig. 5.11(b) & (c)) can operate at a lower frequency with the same unit cell size. In order to design a basic square
loop which can resonate at 5.4 GHz, the element unit cell size, $L_1$ needs to be 10.6 mm. Thus an area reduction of 53.86% for the same frequency was achieved by meandering the element. The overall FSS structure was further modified by screen printing (Fig 5.11(c)) on the reverse of the dielectric substrate. When a linearly polarized plane wave impinges upon the structure, positive and negative charge densities are accumulated on the top and bottom sides respectively, creating the additional mutual capacitance, $M_c$ and mutual inductance, $M_l$ between the two surfaces. The combination therefore acts as a parallel combination of two series LC resonators, having stop band characteristics.

**Table 5.3:** The effect of meandered element on the transmission response of the FSS.

<table>
<thead>
<tr>
<th>Stages</th>
<th>No. Meanders, $n$</th>
<th>Track length, $L_2$</th>
<th>Res. Freq, $f_r$</th>
<th>Bandwidth, $BW$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basic Model</td>
<td>0</td>
<td>0.23$\lambda_r$</td>
<td>8.7 GHz</td>
<td>3.2 GHz</td>
</tr>
<tr>
<td>1$^{st}$ convolution stage</td>
<td>4</td>
<td>0.16$\lambda_r$</td>
<td>6.06 GHz</td>
<td>1.4 GHz</td>
</tr>
<tr>
<td>2$^{nd}$ convolution stage</td>
<td>12</td>
<td>0.14$\lambda_r$</td>
<td>5.4 GHz</td>
<td>1.2 GHz</td>
</tr>
</tbody>
</table>

* $\lambda_r$ is the resonant wavelength of each FSS as defined by the resonant frequency.
** $n$ is counted as the inward depths in the FSS element.

### 5.5.3 LAYER OFFSET (only bottom surface)

The filtering response of a single layer FSS is known to suffer from a narrow bandwidth in high inductance and low capacitance designs. The most common technique to increase the bandwidth and improve the filtering response is by increasing the number of FSS layers with the inclusion of a dielectric spacer [24]. From [23] and [25], it is seen that various offset techniques can be used to change the coupling coefficients and the bandwidth of a double-layer FSS. Implementing the concept of an offset layer technique as discussed...
In the beginning of this chapter, three meandered configurations were considered in which elements on both sides of dielectric had:

1) the same shape aligned with no offset on the bottom surface and meanders, \( n = 12 \).

2) the same shape with both axes offset by a half period on the bottom surface and meanders, \( n = 12 \).

3) the complementary shape with both axes offset by a half period on bottom surface and meanders, \( n = 16 \).

For all cases, Fig 5.11(c) serves as the top side FSS element and the bottom side was shifted in both \( x \) and \( y \) axes simultaneously, as shown in Fig 5.13(b) & (c). The relative lateral displacement proved to be important in the design as it affects the mutual inductance and capacitance of the conducting elements [25].
The analysis shows that the shape from Fig. 5.13(c) in which the number of meanders is \( n=16 \), has a lower stop band and a broader bandwidth compared to the \( n=12 \) configurations, the reason being that the lumped inductor and lumped capacitor in the double-sided FSS were placed in a manner that maximum coupling to the electric and magnetic field of the incident plane wave was achieved. The results are tabulated in Table 5.4.
Table 5.4 Normal incidence response for various offset bottom surface configurations.

<table>
<thead>
<tr>
<th>Configurations</th>
<th>Offset Values</th>
<th>$f_r$(GHz)</th>
<th>$\text{-10dB BW}(\text{GHz})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SS, $n=12$</td>
<td>$\delta x$, $\Delta y$</td>
<td>5.40 GHz</td>
<td>1.20 GHz</td>
</tr>
<tr>
<td>DS same shape, $n=12$</td>
<td>0, 0</td>
<td>6.40 GHz</td>
<td>1.80 GHz</td>
</tr>
<tr>
<td>DS same shape, $n=12$</td>
<td>0.5$L_1$, 0.5$L_1$</td>
<td>5.98 GHz</td>
<td>1.94 GHz</td>
</tr>
<tr>
<td>DS same shape, $n=16$</td>
<td>0.5$L_1$, 0.5$L_1$</td>
<td>1.89 GHz</td>
<td>2.23 GHz</td>
</tr>
</tbody>
</table>

*SS- Single sided; DS-Double sided; $n$-no. of meanders.

5.6 THE MEANDERED DOUBLE SIDED FSS

Using the meandering and offset layer approach, the new double sided FSS was fabricated and calibrated. The major feature of this structure is the homogeneity in terms of filtering characteristics, i.e. the angular stability of resonant frequency. The application of thin substrates increased the coupling between the elements of the structure. In addition, the cascading of these FSS layers show that the frequency was reduced and the bandwidth widened.

5.6.1 Prototype fabrication and measurements

Following the physical specifications mentioned in Table 5.1, the double sided meandered FSS was fabricated using the screen printing technology. The conductive elements were printed on the substrate using a silver ink with $\sigma = 4.3 \times 10^6$ S/m and thickness 10 µm. The prototype sheet was 23 cm × 28 cm in size and consisted of 28 × 35 number of elements fabricated on 0.21 mm (210µm) thick polycarbonate substrate with permittivity of 3.2 and loss tangent of 0.0025, as shown in Fig 5.14.
The screen printed FSS showing the two surfaces of the FSS. On left is the top surface with unit cell showing zero offset and on the right is the bottom surface with unit cell showing two axes offset. Both surfaces are of equal size 230 mm x 280 mm. (Units = mm)

The measurement was carried out in a microwave anechoic chamber. Standard horn antennas were placed 60 cm from the sample, each connected to a vector network analyser (VNA) interfaced for S-parameter measurements. The schematic diagram and the actual experiment set up are shown in Fig. 5.15.

Figure 5.14. The screen printed FSS showing the two surfaces of the FSS. On left is the top surface with unit cell showing zero offset and on the right is the bottom surface with unit cell showing two axes offset. Both surfaces are of equal size 230 mm x 280 mm. (Units = mm)

Figure 5.15. Schematic diagram and the experimental set up for measuring the transmission and reflection characteristics.
The measurement was performed in two steps: (a) calibration was achieved by eliminating the losses in the cable and foam by measuring the $S_{11}$ and $S_{21}$ between the two horns without the sample. (b) The diffraction around a metal sheet with the same size as the sample was subtracted from subsequent sample measurements.

5.6.2 Transmission response at normal angle ($\theta=0^\circ$)

The FSS was assumed to be an infinite periodic flat structure with unit cell boundary conditions in the $x$, $y$ directions and fields expanded as a set of Floquet ports. The unit cell was excited by an incident plane wave with different polarizations and different angles of incidence. The stop band for the double-sided FSS was centered at 1.89 GHz in both simulated and measured results as shown in Fig 5.16. There were some differences in the insertion losses which might be because of the air gap, misalignment, dielectric loss, calibration accuracy and measurement tolerances at such a relatively low frequency band. The approximation of the conductivity of the dry ink (silver paste) can cause the slight discrepancy as well.

![Figure 5.16](image-url)  
**Figure 5.16.** Transmission and reflection response for the double sided FSS with two axis offset, at normal plane wave incidence.
5.6.3 Angle and Polarization sensitivity at off normal angles of incidence ($\theta > 0^\circ$).

When the electric field is perpendicular to the plane of incidence, the polarization is termed the transverse electric (TE) polarization and when it is parallel to the plane of incidence the polarization is termed the transverse magnetic (TM) polarization [26]. The sensitivity of the frequency response of the single-sided and double sided FSS prototype was measured at incident angles ranging from $15^\circ$ to $60^\circ$ for different polarizations, as shown in Fig 5.17. These measurements were made over a frequency range of 1 GHz to 12 GHz. It is evident from Fig 5.17 (a) that for the single-sided FSS and with TE polarization, a wider band performance was achieved and the frequency shift was $<6.7\%$. However, for TM polarization, the band edges were nearly the same as those at the normal incidence with a frequency shift of $<3\%$ (see Fig 5.17(b)). As evident in Fig. 5.17 (c), the centre frequency of operation of the double sided FSS does not change significantly ($<3\%$) as the angle of incidence increases from $0^\circ$ to $60^\circ$ for TE polarisation. However, as the angle of incidence changes, the bandwidth gets wider. The ripples in the response curves beyond 8 GHz were due to multipath fading inherent in the test environment. For TM polarisation, the transmission response for higher angles starts to drift slightly ($<6.4\%$) beyond the centre frequency obtained at $\theta = 0^\circ$ (see Fig 5.17(d)). There was little effect on the bandwidth and the band edges.

Despite the difference in insertion losses which can be due to dielectric and conductive losses, a good match was obtained between the simulated and measured results in this experiment for the double sided FSS. This further verifies the stable behavior of this miniaturized low profile FSS.
Figure 5.17. Comparison of measured and simulated frequency selective characteristics at normal and oblique angles (a) Single sided FSS TE polarization (b) Single sided FSS TM polarization (c) Double sided FSS TE polarization (d) Double sided FSS TM polarization.

5.7 CASCADED FSS SCREENS

The design of band stop filters with large bandwidth is usually a big challenge [14]. The meandered double sided FSS is a low profile shielding surface with stable angular properties.
5.7.1 Improved Bandwidth

A considerable bandwidth was achieved by placing two FSS arrays in free space positioned in parallel planes.

Figure 5.18. (a) Transmission curves for normal angle of incidence for single layer double sided (SLDS) FSS and cascaded FSS with array separations, $D = 2 \text{ mm} \ (-0.01\lambda_r)$, $5 \text{ mm} \ (-0.02\lambda_r)$, $7 \text{ mm} \ (-0.04\lambda_r)$, $10 \text{ mm} \ (-0.06\lambda_r)$ respectively where $\lambda_r$ is the resonant wavelength. The gap between the two FSS screens was filled with free space, dielectric constant, $\varepsilon_r=1$. (b) Bandwidth variation over a range of separations between the two FSS arrays. (c) Layout of cascaded configuration.
The simulated transmission coefficient for a single layer FSS compared with the cascaded FSS is shown in Fig. 5.18(a). The band stop frequency for the different cases remains centered at 1.89 GHz. However, the sharpness of the transmission curve was improved by cascading the two FSSs. The lower limit frequency \( f_L \) of the transmission curve shifted slightly whereas the upper limit frequency \( f_H \) exceeds the single layer value from 3.34 GHz to 6.18 GHz, providing a broader -10dB bandwidth (55.6%) compared to the non-cascaded FSS. The two identical double-sided FSS arrays separated by 0.04 \( \lambda_r \) corresponding to 7 mm could be used to improve the shielding of cellular communication signals through glass or perspex windows of appropriate thickness. The bandwidth analysis was performed over larger separations between the two double sided FSS ranging from 2 mm (~0.01\( \lambda_r \)) to 80 mm (~0.5\( \lambda_r \)), as shown in Fig. 5.18(b). A cyclic effect was evident in bandwidth variation with thickness due to the multi layering of FSSs and the standing wave generated by the electromagnetic fields in the separation region coupling the energy from one FSS to the other. Fig 5.18(c) shows the generalized portrayal of the cascaded configuration in which the double sided single layer FSS was spaced from an identical corresponding FSS. This concept of cascading FSS screen can be applied in practice to the double layer glass structures also called double glazing (in which two float glasses are separated by a gap) in office buildings. The FSS can be deployed on two sides of the office windows shielding the radio waves.

Further, for the broadband applications with less structural or space constraints, more FSS screens can be cascaded in a multilayer arrangement at the predetermined spacing or filled with appropriate dielectrics to widen the band stop regions.
5.8 SUMMARY

This chapter discusses the various advantages of the simple and meandered square loop double-sided FSS. The square unit cell FSS exhibits a -10 dB stop bandwidth of 8.22 GHz ranging from 4.55 to 12.77 GHz. The FSS is an array of square loops on the top side and an identical array displaced on the bottom side of the dielectric substrate. The resonant frequency of the metallic loops is decreased from 9.14 GHz to 7.60 GHz and the bandwidth can be doubled from 4.27 GHz to 8.12 GHz. The dimensions of the FSS elements are much smaller ($\lambda_o/5$) than the operating wavelength. The effect of various physical parameters used to improve the bandwidth of FSS was also reported. The bandwidth can be reduced or enhanced by optimizing the three parameters of the structure: substrate thickness, inter element spacing and track width. The simple printed FSS geometry on a transparent substrate retains the optical translucency and RF transparency required in many applications. A part of this work has been published in [23]. In the latter half of this chapter, a miniaturized frequency selective element implemented on two sides of a single layer substrate using screen printing technology with a stop band intended to shield cellular frequencies was presented. In comparison to the references [18-21], a significant reduction in stop band frequency (1.89 GHz) has been achieved by the proposed miniaturized FSS. The unit cell size of the proposed FSS of $0.045\lambda_o \times 0.045\lambda_o$ has been significantly reduced in comparison to this earlier work. The basic square loop was optimized by meandering the sides and then offsetting the bottom surface FSS on the dielectric substrate in a manner that the element tracks superimpose and the structure behaves like a lumped element model with increased mutual coupling. Experimental results are in good agreement with the simulations, thereby validating the design concept for GSM applications in radomes and other microwave systems. The success of the design is a result of the
maximum coupling achieved by offset techniques. The sensitivity of the response of the designed FSS to the normal and oblique angle of incidence, and to both TE and TM linear wave polarizations, was analyzed. Apart from the miniaturized element, reduced resonant frequency and the angular stability up to 60°, the -10dB bandwidth of the proposed FSS structure can be controlled and extended out to 1.20 GHz – 3.34 GHz and can be further enhanced by cascading the two identical FSSs without changing the stop band frequency. By virtue of its flexible nature, low manufacturing cost and easy mass production, the designed conductive FSS can be rolled into long continuous sheets of wall paper and used in frequency shielding over walls/windows. It is also applicable for shielding conformal surfaces. Part of this work has been published in [27].
5.9 REFERENCES


CHAPTER 6

APPLICATIONS

6.1 ROOM ISOLATION

6.1.1 INTRODUCTION

The number of wireless networks continues to increase with time. In buildings, picocellular communications, wireless sensor networks (WSN) and mobile telephone bands must co-exist. While operating at very different frequencies, the challenge remains to ensure good connectivity for large area networks and well defined spatial limits for pico cellular networks and WSN. There is also some interest in room isolation for data security. Frequency reuse and network security are two drivers to pico cell isolation. A coating of metamaterial [1] is one option available to solve this problem, however the fabrication and installation costs to cover large wall areas must be very low to be economically viable [2]. As building materials include wood, paper, concrete and glass, a general purpose FSS which has similar isolation properties when placed against all of these materials is of interest.

A FSS is a type of metamaterial, which can be designed for band-reject transmission of microwave signals and is suitable for pico cell isolation [3]. In the case of room isolation, the band stop frequency of the surface is most important, as it allows isolation of adjacent rooms for reuse of one common LAN while other frequencies pass through the walls of the room with minimum attenuation. The ability to print conductors on a low cost, flexible plastic sheet means that installation on the walls and ceiling is relatively simple, and might
even be incorporated into the wall materials themselves [4]. For example, prefabricated wall paneling could include the FSS structure without a significant increase in weight, volume or utility.

This section discusses a printed FSS for picocell isolation inside a room. As the structure has no ground plane, the centre frequency of the stop band can be influenced by the electromagnetic properties of the wall materials the thickness of the wall. The effects on the FSS centre frequency was investigated for different target objects. The permittivity range of $1 < \varepsilon_r < 10$ and different thickness, $d$, are reported. While FSS characteristics have been reported previously, these studies have not commented on the FSS frequency changes with different wall materials. The effect of various objects on the resonant frequency of printed RFID antennas has been reported [5], however, no simple calculation method exists to predict the change in resonant frequency. For this reason a full 3D electromagnetic modeling tool was required.

The bandwidth is normally defined by -10 dB level in transmission and 0.5 dB level in reflection for the stop band FSS. However, there are certain applications such as FSS used in prisons for shielding the cellular frequencies or in medical equipment like magnetic resonance imaging devices where the signals are large in amplitude, a stop band attenuation of more than 10 dB is required.

6.1.2 SCREEN PRINTED FSS FOR ROOM ISOLATION

6.1.2.1 FSS Geometry

The analysis is based on the FSS ring type (Chapter 4). The rectangular array of rings was silver printed on a plastic substrate. This acts as a band stop filter. Fig. 6. 1 shows the dimension of the unit cell. The ring has width, $w = 0.26$ mm and radius, $r = 3.1$ mm on a
flexible thin plastic substrate of $\varepsilon_r = 3.2$ with substrate thickness of 0.21 mm. The structure was modeled using a plane wave source excited normal to the plane of the conducting ring. The transmission properties were evaluated as a function of frequency of the incident radiation. Parker et al [6] found that circular ring elements are less sensitive to incident angles when compared to other shaped elements. On varying the angle of incidence from $0^\circ$ to $50^\circ$, the general features of the stop band stay the same as that for normal incidence. For the TE mode transmission, the higher order resonances move closer to the resonant frequency, whereas for TM mode transmission, higher order resonances start moving away from the resonant frequency.

![Figure 6.1](image)

**Figure 6.1** Unit cell of the FSS structure consisting of a printed silver ring on top of a thin flexible plastic substrate and backed by target object.

The transmission characteristics of the structure in air (i.e. setting the target object properties to those of air $\varepsilon_r = 1$ and the conductivity $\sigma = 0$), are plotted in Fig 6.2 as a function of frequency. The 10dB bandwidth is 10.5 GHz to 14.2 GHz and is approximately symmetrical about the centre frequency at 12.35 GHz. This band stop frequency changes with the substrate relative permittivity $\varepsilon_r$. Clearly if the properties of substrate and the object are both known, the structure can be optimized for a required frequency. In many cases, the
electromagnetic properties of the object are not known, and can vary across the structure due to the addition of supporting beams and wall coatings.

**Figure 6.2** FSS transmission coefficient on a substrate with \( \varepsilon_r = 1 \) and thickness 0.21 mm. The 10 dB bandwidth is approximately 3.5 GHz.

### 6.1.2.2 FSS on different target objects

When the FSS on a very thin substrate is placed on an object, the stopband frequency will change due to the different values of \( \varepsilon_r \). The variation in the stopband frequency is shown in Fig.6.3 as a function of \( \varepsilon_r \) for a wall thickness of 2mm. The center frequency decreases monotonically as the relative permittivity increases. For \( \varepsilon_r > 4 \), the frequency shift is greater than the original bandwidth of the structure. This change is similar to the change in resonant frequency of a planar dipole antenna on a very thin substrate [7].
The analysis was extended to observe the effect of changing thickness $d$ of the target object. Fig 6.4 shows the variation in the stopband frequency with object thickness $d$. This range was designed to include most common materials used in wall, door and window construction. Thus the target object thickness $d$ was increased from 1 mm to 20 mm for wood, concrete, glass and paper. The results shows there is no significant change in frequency shift when the $d$ changes. Note that the quantization in the frequency axis is the result of a computational resolution in frequency of 0.1 GHz.

The very minor change in the FSS stopband frequency for $d > 1$ mm demonstrates that the thickness of the object is not an important parameter in the attenuation of the signal. Clearly the effect of the thickness on the capacitance between the rings is minimal if the
printed rings are located on the outside of the films and not between the substrate and the object.

**Figure 6.4** FSS stopband frequency variations on different objects: wood ($\varepsilon_r = 4$), concrete ($\varepsilon_r = 6$), paper ($\varepsilon_r = 8$) and glass ($\varepsilon_r = 10$) [8] as a function of the thickness.

As the thickness of target object has no significant effect on the FSS stopband frequency, the effect was dominated by the change in relative permittivity. Fig. 6.5 shows the transmission coefficient of the FSS on substrate with and without the target object. The FSS without target object was similar to Fig. 6.2 and has a 3.5 GHz bandwidth. With an object with $\varepsilon_r = 10$, the bandwidth decreases to 2.5 GHz. Fig. 6.5 clearly demonstrates that the change in the centre frequency of the stopband was well outside the bandwidth of the FSS in air. This is of significant importance in room isolation technologies. The printed FSS sheets designed for use on wood and concrete will not function satisfactorily when placed on glass.
Figure 6.5 FSS without target object (continuous line) and on $\varepsilon_r = 10$ (o). The bandwidth was reduced by approximately 1 GHz. This plot demonstrates that this FSS can not be used effectively on these two different materials.

The transmission coefficient ($S_{21}$) was measured using two X-band pyramidal horn antennas placed 30 cm apart facing each other and 14.5 cm from the ground. The sample materials were placed halfway between the two horns and the response was measured as a function of frequency. The system was first calibrated using a free space path. The maximum generator frequency was 11.2 GHz and the sensitivity of the receiver was -35 dBm. Fig.6.6 shows that the attenuation ($S_{21}$) characteristics when the thin plastic FSS was placed on wood and glass. The measured free space path loss is the function of frequency. The $S_{21}$ transmission characteristics for FSS on two different materials (wood and glass) were calculated by subtracting the free space variation ($\text{Wood}_{\text{FSS}} - \text{Foam}_{\text{plastic}}$) and so the glass with FSS ($\text{Glass}_{\text{FSS}} - \text{Foam}_{\text{plastic}}$). The wood without the FSS was found to be frequency independent and has a mean absorption loss of 2.03 dB. The loss through glass was also
frequency independent and has a mean loss of 0.58 dB. Note the thickness of substrate, \( t \) was always less than 0.1\( \lambda_0 \).

**Figure 6.6.** \( S_{21} \) experimental results showing effect of the FSS on wood (thickness =20 mm) and glass (thickness = 10 mm) compared to the wood and glass alone. The continuous line is the free space characteristic. The materials without the FSS coating show very little change with frequency.

While the frequency range of the equipment was limited to below the stopband frequency, a statistical t-test was used to assess the difference between the two data sets. The results generated by this test are pooled variance, an accumulated measure of the spread of data about the mean, which is calculated from this formula:

\[
S^2 = \frac{n_1 S_1^2 + n_2 S_2^2}{n_1 + n_2 - 2} \quad (6.1)
\]

where \( n_1 \) and \( n_2 \) are the number of observations for wood with the FSS and glass with the FSS respectively. \( S_1 \) and \( S_2 \) are the mean values for the wood and glass respectively. The results showed that there is 80% level of significance to support the hypothesis that the
mean test values of two target objects are different. However, it is clear that the stop band center frequency was greater than 11.2 GHz for both wood and glass materials, but the shape of the curve was convincing that there is a clear stop band for both materials resulting from the FSS. The future trends and developments for this visibly thin transparent low cost FSS wall/window configuration is discussed in next chapter.

6.2 FSS WINDOWS SHIELDING UMTS 2000 MHz.

6.2.1 INTRODUCTION

The received radio signal in a typical indoor environment is mainly attenuated due to the reflections and transmissions through building materials. The penetration loss depends on the electrical properties, structure, and periodicity of the building material. In a previous section, the propagation through a ring resonator on various target objects used as building materials like concrete, wood, glass were investigated. This work is complementary to that, focusing more on introducing FSS windows which can find application in offices, prisons, military base stations, buses and trains, etc. The properties such as transparency of the film, easy installation on the glass, no structural loading due to its thin and flexible nature, and confinement of certain frequency bands of electromagnetic spectrum as per the desired applications are discussed in the latter half of this section.

Good transmission of RF/Microwave signals is possible through a standard glass sheet, with low conductivity ($\sigma=10^{-12} \text{S/m}$), relative permittivity ($\varepsilon_r=10$) and thinner than the operating wavelength. Most of these microwave signals fall within the frequency band 800 MHZ to 2200 MHZ, covering mobile phones, GPS, 3G/Wireless broadband, GSM and personal communication systems (PCS). Inspired by the unique properties of frequency
selective surfaces, this work explores the use of screen printing technology to realize a band stop shield at desired frequencies which can be easily applied on the windows.

When a plane wave illuminates a frequency selective surface (FSS) it functions as a passive electromagnetic filter, either band stop or band pass depending on the structure used. Besides finding their application in military such as the design of reflect array lenses and radomes [1][9, 10], recent work and study of use of FSS to improve the propagation through buildings has been of great interest [11]. The use of FSS in low emissivity windows for indoor to outdoor communication was studied in [12, 13]. However, there were a few issues like drilling the hexagonal slits on the metallic coating of the thermal glass which caused deviations from the original design due to deep engraving. Also the measurements were done over 400 × 400 mm² and not actual standard window size. Though the authors presented interesting results and ideas of FSS design but the value of one of the important physical parameter of the FSS design such as dielectric permittivity was based on assumption and not an exact value.

In this section, we propose an FSS window, which is tuned to shield the UMTS 2000 MHz frequency band without affecting the other frequency bands. The single layer planar two-dimensional periodic structure is composed of modified square loops in order to realize the FSS miniaturization. The miniaturized element overcomes the restriction of limited space and improves the angular stability of the frequency response of the surface [14]. The desired behavior is obtained by modifying each segment of the square FSS into inward-outward peaks (as discussed in Chapter 4) arranged in a square lattice geometry.

This section also highlights the industrial application of this novel large FSS window to block the UMTS frequency band. However, the structure can be tailored for shielding of
the desired frequency band. In order to improve the optical transparency, less complex elements like square loops or rings can be used instead or finer track dimension may be implemented using more elaborate printing technique. The performance of practical FSS structure with and without glass is included in order to confirm the accuracy and validity of the prototype. The full wave simulations are done by CST Microwave Studio and all measurements are carried in an anechoic chamber.

6.2.2 SELECTION OF FSS ELEMENT

The design approach and the physical specifications of this meandered FSS are explained in Chapter 4, Section 4.5.1 and Section 4.5.2 respectively and will not be repeated here. The physical parameters and dimensions are given in Table 4.2. However, the dielectric substrate used for the purpose of investigation is PET (Polyethylene terephthalate). It provides transparency, excellent flexibility and is robust in nature. The PET has a thickness of 0.038 mm and relative permittivity of \( \varepsilon_r = 3.4 \). Using the screen printing technology, the FSS is printed on one side of the substrate and on the other side is an adhesive which helps in bonding of FSS screen on large window panes. However, care needs to be taken when bonding the film onto the window so that the bond is uniform without any bubbles or deformations which can degrade the performance and efficiency of the FSS.

Silver paste (\( \sigma = 4.3 \times 10^6 \) S/m) is used to print the pattern on the PET and has a thickness of 0.01 mm. The conductivity of silver paste is lower than the actual silver due to the presence of adhesive and slider powder [15]. Despite, besides the close segment packing of convoluted elements, transparency is retained by reducing the conductor (metal) widths. The Fig. 6.7 shows the amount of transparency through glass retained even after
putting the FSS film on the glass. However, if the space limit is not an issue and miniaturized structures are not required, loop structures such as rings, square loops, hexagons can be utilized.

**Figure 6.7.** The picture shows the amount of transparency still retained after the close element packing of Miniaturized convoluted square loops which can be further enhanced by using less complex elements affecting the miniaturized nature of the overall structure.

### 6.2.3 MEASUREMENT SET UP

In order to characterize the FSS response and validate the manufactured large prototype, measurements were carried out in the anechoic chamber at Griffith University. The fabricated FSS contained $128 \times 98$ elements printed on one side of the substrate, as seen in Fig 6.7. Two linearly polarized, wideband dual ridged horn antennas were used for measuring the transmission through the large band stop FSS screen and finally through the screen on glass as well. A vector network analyzer (Anritsu MS46122A) was used to sweep
the frequency between 500 MHz - 5 GHz to obtain $S_{21}$. Fig. 6.8 shows the measurement set-up which consists of a wooden two-legged holder, wooden frame holding the FSS, glass, or both, of exactly the same size. As discussed in Chapter 3, Section 3.5 before measuring the FSS sample, various calculations need to be done in order to make sure the FSS lies in the far field region of the two antennas. The estimated far field distance is $d_{\text{farfield}} = 77$ cm, with the FSS located centrally between the two antennas, with maximum dimension of the horn antenna being 240 mm. The calculated horizontal beam width is $32^\circ$ and vertical beam width is $52^\circ$.

**Figure 6.8.** Photograph of the measurement set up for measuring the FSS window.

The 128 x 98 convoluted square loops were printed on one side of PET bonded on the glass window pane which is fixed in a wooden frame positioned between the two horn antennas.
6.2.4 RESULTS.

The validity of this concept is demonstrated by numerical simulations and experiments. The plane wave transmission through various substrates have been investigated by placing blank PET sheet, glass only, FSS on PET and small and large FSS screen bonded on standard window float glass between the horn antennas, as shown in Fig 6.9.

![Figure 6.9](image)

**Figure 6.9.** The plot shows the measured plane wave transmission response at normal incidence (0°) of all cases investigated. The transmission loss increases from 60 dB to nearly 72dB when the large FSS is bonded on the glass. The FSS alone resonates at 2 GHz which decreases to 1.14 GHz by placing FSS on glass.

For analysis both small FSS (28 cm × 26 cm) and standard window size large FSS (1170 cm × 1540 cm) were measured. Both the structures blocked the transmission at the
same notch frequency 2 GHz. However, the response of the small screen was calibrated and shown in Fig 6.10. The transmission calibration was further done by subtracting the transmission from the transmit antenna to the receive antenna through the air gap, from the FSS only (isolation) in order to normalize the $S_{21}$ response. The simulated results for the FSS are obtained by unit cell boundary conditions assuming the structure to be infinite in size. The dimensions of the convoluted square loop are chosen such that they resonate at 2000 MHz with 1.3 GHz bandwidth, which is enough to attenuate the UMTS 2000 MHz transmission signals. The measured transmission response shows high transmission loss of nearly 22 dB at 2 GHz, as shown in Fig. 6.10. However, the transmission loss in the measured case is less than the simulated results due to the diffraction from the edges of the measurement set up. The measured and simulated results are in good agreement, which proves the validity of the manufactured prototype.

![Figure 6.10](image)

**Figure 6.10.** The plot shows the normalised measured and simulated transmission response at normal incidence ($0^\circ$) of the small screen FSS.
To ensure the precision of the experiment, the response is normalised by subtracting the $S_{21}$ parameters when nothing is in between the two horn antennas from the $S_{21}$ parameters where only the FSS is the middle.

![Graph](image)

**Figure 6.11.** The effect on the $S_{21}$ of standard float glass with and without FSS. The FSS placed on the glass adds inductance to the transmission line model of this FSS structure (discussed in Chapter 4), thereby decreasing the resonance of the structure.

Adding a thick dielectric on one side of the FSS decreases the resonant frequency of the overall periodic structure [2]. The impact on the behaviour of a standard float glass with and without an FSS shield is illustrated in Fig. 6.11. A strong resonant frequency at 1.15 GHz with transmission loss of nearly 38 dB is observed in the simulated response. However, the measured results show 28 dB attenuation at the stop band frequency of 1.14 GHz is achieved. There is a slight difference in the measured results which may be due to
the misalignment of the measurement set up or the finite size of FSS and glass, which was assumed to be infinite in the simulations.

6.3 SUMMARY

A ring type frequency selective surface (FSS) can provide transmission stop-band characteristics in rooms. This allows adjacent rooms to be isolated for one LAN for frequency reuse while other frequencies pass through the walls with minimal attenuation. The FSS was screen printed on a thin flexible plastic substrate of permittivity 3.2 with a stop band at 12.3 GHz and 10 dB bandwidth of 3.5 GHz. The variation in band stop characteristics was investigated for various wall/window materials. The centre frequency varied by more than 3 GHz for common wall/window materials which means significant transparency for some building materials. The technique is a low cost method of confining LAN picocells in one room. A major part of this work was published in [16]. The screen printed technology was further used to explore the potential application of shielding the UMTS 2000 MHz frequency band while allowing all other bands to pass through the FSS window pane. The shielding surface is an array of modified convoluted square on a flexible transparent substrate bonded on the glass. The transmission through unprinted and printed substrate with and without glass was investigated. With the optimized FSS design, good agreement was achieved between the theoretical and experimental results. However, the notch frequency depends on the permittivity and thickness of the glass, and also the angle of incidence. The FSS design can be tuned to the shield various frequency bands by rescaling various physical parameters of the element.
6.4 REFERENCES


CHAPTER 7

CONCLUSION AND FUTURE DEVELOPMENTS

7.1 SUMMARY OF RESEARCH

The introduction of the screen printing technology in the design of the microwave, spatial filters for shielding communications applications is the main advance of this research. The new approach has provided new frequency selective surfaces with enhanced filtering capacity, conformal nature, and transparency. The analysis gives a physical insight into the behavior of these surfaces. This chapter discusses the future developments that need to be addressed in order to realize the frequency selective surface on windows as a practical commercial product. This summary is reported as outcomes from the various chapters of this thesis.

Chapter 4

The comparative study of S-parameters of a ring FSS structure on a plastic (polycarbonate) dielectric substrate showed a good agreement between measured and simulated results, supporting the viability of polycarbonate film as a backing substrate for printed FSS. From the S_{21} measurements it was observed that as the substrate thickness was increased, the stop band rejection frequency decreases. For a substrate thickness greater than 1.8 mm, the resonant characteristics remains unaffected and so thick substrates can be replaced by thin films for the same frequency response. For example, 1.6 mm thick FR4 PCB could be replaced with 0.4 mm transparent polycarbonate sheet and maintain the same
resonant frequency. Conversely, an even thinner sheet could be used with a higher frequency, or the structure could be enlarged to maintain the same frequency properties. The bandwidth of the FSS structure shows a cyclic effect due to the change in substrate thickness. Therefore, a wide band gap can be obtained even for thin plastic substrates. The thin flexible plastic substrate allows FSS structures to have a multitude of applications such as in scanned phase arrays, conformable shielding devices in GPS, in cockpit windows needing frequency selective properties and platforms for military vehicular antennas. Various office environments make use of pico-cellular wireless communications such as personal handy phone system where in order to improve the efficiency each room needs to prevent leakage of radio waves into and out from the room. The shielding of windows, floors and ceilings of each room by an FSS can overcome this problem.

The concept of meandering the square element single layer frequency selective surface (FSS) was presented in the latter half of this chapter through the discussion on the physics involved. The meandered square loop single layer FSS has practical features of interest such as:

1) Transparent, conformal, flexible thin frequency selective surface.
2) Reduced unit cell area with reduced stop-band frequency. Potential GPS frequency shielding application.
3) Low sensitivity of spectral response to wide angle of incidence and different polarizations.
4) Improvement in signal propagation through glass using the designed FSS.
Chapter 5

The bandwidth characteristics of the square loop frequency selective surface discussed briefly in chapter 4 were investigated further in this chapter. The approach of multi layering and the lateral offset alignment in both directions was used in order to achieve the wide stop band characteristics suitable for UWB applications. The design provides a 10 dB insertion bandwidth of 4.55 - 12.77 GHz. The design delivers a stop band independent of most of the angles of incidence in both single sided and double sided configurations up to 60° degrees. The symmetrical nature ensures an identical response for TE and TM modes of polarization within 30° incidence. A comprehensive iterative analysis using various physical parameters of the FSS was made to increase the bandwidth.

Miniaturized FSS design with selective transmission, optical translucency and shielding at frequencies such as mobile communication signals (GSM) working around 1.89 GHz for window configurations was also presented in this chapter. A novel low profile, thin, flexible and semitransparent dual layer frequency selective surfaces (FSSs) operating in L-band have been designed and fabricated using the screen printing technology. The composite FSS structure was achieved by meandering the basic $\lambda_o/22$ square loop at its four corners filling the space on the top layer and half period offset pattern on the bottom, which produces a reject band in the lower microwave spectrum at 1.89 GHz. An offset technique is more complex as compared to the single layer square loop discussed in Chapter 4; because of the density of elements in this FSS structure. The measured and simulated frequency response of the FSS structure for both single and double
sided FSS, for TE and TM polarizations, at various angles of incidence showed good agreement.

**Chapter 6**

A low cost FSS created by printing silver on a thin, flexible, plastic substrate and placed on various target objects was assessed for the building industry. The relative permittivity of the target object can have a large and significant impact on the FSS band stop center frequency. The thickness of the target object showed little effect on the band stop resonance. The bandwidth reduced with increasing values of $\varepsilon_r$, particularly on high $\varepsilon_r$ objects. This work demonstrates that the printed FSS can provide good isolation in a room if the object is designed for and placed on one particular type of building material. When there are a number of different object materials, then the bandwidth might be too narrow to accommodate the large variations in the centre stopband frequency. This means that there will be significant microwave transmission through the windows.

There are two possible strategies to overcome this problem:

a) The FSS needs to be constructed in such a manner that the bandwidth is increased. This can be achieved using differently sized FSS conductive rings on the same substrate. This needs further investigation.

b) The FSS needs to be designed specifically for the target objects. Thus a prefabricated wall will have one geometrical structure and the windows must have another. The wall FSS will have a different stopband characteristic in free space compared to the glass FSS. When these FSS coatings are applied to the different materials enclosing the room, the stopband frequency is the same.
The printed FSS has very good transparency so the windows remain transparent. The size and thickness of the conductive tracks is similar to the effect of insect screens commonly used in buildings.

### 7.2 COMPARISON OF PERFORMANCE

The comparison of performance of various designed FSS prototypes is tabulated in Table 7.1. The frequency characteristics of these FSS structures can be tailored for desired applications by optimizing their physical parameters.

**Table 7.1** Different FSS configurations and their respective spectral response.

<table>
<thead>
<tr>
<th>FSS Type</th>
<th>Single Layer Ring Resonator</th>
<th>Single Layer Meander Loop</th>
<th>Double Layer Square Loop</th>
<th>Double Layer Meander Loop</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structure</td>
<td>Single Layer FSS</td>
<td>Single Layer FSS</td>
<td>Double Layer FSS</td>
<td>Double Layer FSS</td>
</tr>
<tr>
<td>Substrate Thickness (mm)</td>
<td>0.21mm</td>
<td>0.21mm</td>
<td>0.21mm</td>
<td>0.21mm</td>
</tr>
<tr>
<td>Unit cell size (mm)</td>
<td>7.53mm</td>
<td>12mm</td>
<td>8mm</td>
<td>8mm</td>
</tr>
<tr>
<td>Resonant Freq.</td>
<td>12.5GHz</td>
<td>2.35GHz</td>
<td>2.32GHz</td>
<td>--</td>
</tr>
<tr>
<td>-10dB Bandwidth</td>
<td>3.8GHz</td>
<td>3.2GHz</td>
<td>--</td>
<td>8.12GHz</td>
</tr>
<tr>
<td>Transmission Loss</td>
<td>-33dB</td>
<td>-35.3GHz</td>
<td>-29dB</td>
<td>--</td>
</tr>
<tr>
<td>Angular Stability (TE)</td>
<td>--</td>
<td>&lt;1%</td>
<td>&lt;6.5%</td>
<td>&lt;2%</td>
</tr>
<tr>
<td>Angular Stability (TM)</td>
<td>--</td>
<td>&lt;3.3%</td>
<td>&lt;10%</td>
<td>&lt;2%</td>
</tr>
<tr>
<td>Optical Transparency</td>
<td>Transparent</td>
<td>Semi-transparent</td>
<td>Transparent</td>
<td>Semi-transparent</td>
</tr>
<tr>
<td>Comments</td>
<td>-Simple geometry</td>
<td>-Miniaturized</td>
<td>-Double sided</td>
<td></td>
</tr>
<tr>
<td></td>
<td>-Flexible and thin</td>
<td>-Reduced Area</td>
<td>-Simple geometry</td>
<td></td>
</tr>
<tr>
<td></td>
<td>-Reflective in Ku band</td>
<td>-Reflective in cellular</td>
<td>-Ultra wide band</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>bands like Wi-Fi, UMTS 2000MHz.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>-Double sided</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>-Miniaturized</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>-Reflective in GSM bands (DS1800 for mobile communications)</td>
</tr>
</tbody>
</table>
7.3 FUTURE DEVELOPMENTS

In this dissertation, all the designed FSSs can attenuate the transmission at the stopband frequency by less than 15 dB which is considered significant in interference reduction [1]. The prototypes offer reasonably stable angular performance and are visually transparent attracting the frequency shielding applications for windows, but potential further improvements to the prototypes remain. A better approach of combining FSS on windows/walls with absorbers and shielding in an indoor environment rich in multipath fading is required in order to further improve the FSS performance. The flexibility of this substrate makes it advantageous in many applications but the development of an economical technique for mass production of these structures is equally very important. In order to realize the designed FSS as a practical commercial product for window/wall configuration, many aspects need to be investigated and improved such as:

7.3.1 Improvement in FSS Design

a. Each designed FSS in this research resonates at one stopband frequency. The convoluted FSS elements have shown stable response over wide angles of incidence. However, convoluted flexible FSS elements for multi-stopbands or passbands may be desirable in certain frequency shielding applications like in prisons where cellular bands (1.8 GHz) or WLAN (2.4 GHz and 5.8 GHz) transmission can be blocked whereas the handheld transceiver (470 MHz) can function normally. However, in multi-band FSS the band separation and the roll off rate at the resonance need attention.

b. Because of the different element sizes, lattice geometry, complex shapes or multi-layers, the equivalent circuit model for the simple shape may no longer be applicable. New equivalent circuit modelling techniques need to be developed.
c. A new conformal mapping technique needs to be developed which would take into account the effects of out-of-plane ring curvature and the bending properties of these flexible FSSs, further applying them in conformal or non-uniform surfaces.

d. The feature of flexibility of polycarbonate (the substrate) helps it to be rolled into continuous sheets for mass production. However, a less expensive fabrication procedure for printing large area frequency selective screens for windows or walls should be developed. New technologies in laser modified conductive plastics may further improve the technology [2].

### 7.3.2 Improvement in Fabrication Process

a. In this research, an opaque conductive silver ink paste was used to screen print the thin metallic tracks on substrate which retained the optical transparency of the plastic film. However, transparent conductive inks would be ideal for manufacturing completely transparent frequency selective windows.

b. Apart from the geometry of FSS elements, the conductivity of the ink used for printing these elements also governs their spectral performance. Proper investigation of cost and performance of these opaque or transparent inks needs to be done.

c. The curing of ink after application on substrate is not a problem in small A4 size screens which can be easily placed in an oven for set time and temperature. The problem arises when the FSS screen is large such as 1m². Larger ovens or different means of curing need to be adopted or developed. The companies like Japan based Tanaka Holdings are in process of manufacturing silver inks which allow screen printing of circuits without thermal curing and instead are cured by ultraviolet light.
d. Double sided convoluted (complex) element FSS fabrication issues such as misalignment and/or overlap of elements on each side need to be further investigated. An easier and appropriate way of registering the films for two sided printing needs to be developed.

e. The miniaturization of the elements of the FSS is limited by the fabrication process. There is chance of ink bleeding if element width and spacing are small. An approach better than manual screen printing where minimum ink is used to imprint the FSS on substrate without smudging of ink or closure of gaps needs to be developed.

f. The technique for manufacturing wearable antennas [3] can be used in printing FSS on fabrics in order to block the radio transmissions. This development can further help to design frequency selective blinds or curtains which can prove to be tunable FSS as opening or closing positions may control their filtering characteristics.

g. The wireless devices are known for the adverse effects on human body due to electromagnetic radiations. Contrarily, the antenna efficiency is known to degrade due to presence of hand on the device. The flexible frequency selective surfaces can be used to develop an encapsulating surface which can insulate the wireless device from the human body.

h. The properties of the target object (wall or window) of different building materials and dielectric constants might prove to vary with time. Therefore, a robust and multi-functional approach is required to reconfigure the FSS and wall/window configuration in order to maintain the overall frequency selective behavior.
7.4 SUMMARY

This chapter includes the concluding remarks and briefly discusses the future trends for this research. The designed thin, flexible, optically transparent frequency selective surfaces have provided a promising solution for shielding the windows be it a building architecture, or vehicles like buses, trains etc. at certain frequencies of interest. The polarization and angular insensitive FSSs have been developed in this research. It has been found that the FSS element dimensions determines the resonant frequency whereas the shape determines the type of filter such as band stop, band pass etc. The supporting dielectric apart from providing the mechanical strength to the FSS structure can also shift the resonant frequency to certain extent. The effect of increasing the resonant length of an FSS element while maintaining the small unit cell size has been explained. The bandwidth is enhanced by cascading the FSS in double sided and multi-layer configurations. This chapter also provides several possible future developments. Apart from improving the design of the FSS element as per the desired application, more economical fabrication techniques for large scale printing needs to be developed. The proper installation strategy for putting these frequency selective screens on windows or walls with minimum misalignment or overlap in order to improve the wireless system performance is also required. Also FSS with absorbing properties need to be designed in order to reduce the multiple interference reflections which can improve the indoor wireless system performance.
7.5 REFERENCES


APPENDIX 1
Optically transparent frequency selective surfaces on flexible thin plastic substrates
Aliya A. Dewani, Steven G. O’Keefe, David V. Thiel, and Amir Galehdar

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Frequency-selective multilayer electromagnetic bandgap structure combining carbon nanotubes with polymeric or ceramic substrates

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Transparent hybrid inorganic/organic barrier coatings for plastic organic light-emitting diode substrates
J. Vac. Sci. Technol. A 23, 971 (2005); 10.1116/1.1913680
Optically transparent frequency selective surfaces on flexible thin plastic substrates

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A novel 2D simple low cost frequency selective surface was screen printed on thin (0.21 mm), flexible transparent plastic substrate (relative permittivity 3.2). It was designed, fabricated and tested in the frequency range 10-20 GHz. The plane wave transmission and reflection coefficients agreed with numerical modelling. The effective permittivity and thickness of the backing sheet has a significant effect on the frequency characteristics. The stop band frequency reduced from 15GHz (no backing) to 12.5GHz with polycarbonate. The plastic substrate thickness beyond 1.8mm has minimal effect on the resonant frequency. While the inner element spacing controls the stop-band frequency, the substrate thickness controls the bandwidth. The screen printing technique provided a simple, low cost FSS fabrication method to produce flexible, conformal, optically transparent and bio-degradable FSS structures which can find their use in electromagnetic shielding and filtering applications in radomes, reflector antennas, beam splitters and polarizers. © 2015 Author(s). All article content, except where otherwise noted, is licensed under a Creative Commons Attribution 3.0 Unported License.

I. INTRODUCTION

Frequency Selective Surfaces (FSS) have applications in radomes, microwave antennas and electromagnetic shielding. The array geometry, element type and backing substrates are used to optimise the transmission and reflection characteristics. This paper reports investigations into the effect of substrate on an array of printed circular conductors. Consideration is also given to optimising the bandwidth by varying the substrate thickness.

A conducting sheet periodically perforated with shaped apertures or an array of periodic metallic plates on a substrate in one or two directions may constitute a frequency selective surface (FSS). A classical FSS consists of a two dimensional periodic array of certain shapes that are either printed on a dielectric substrate or etched through a conductive layer. These are classified as inductive or capacitive structures. When the periodicity is small compared to the operating wavelength, the FSS can be modelled as an array of equivalent LC circuits. The capacitance results from gaps between the adjacent conducting slots/dipoles and the inductance results from the current along the adjacent dipoles or around the loop area in case of slots. Frequency selective surfaces are periodic resonant structures that behave like a spatial filter. These structures can either block or pass electromagnetic waves of a certain frequency depending on the specific shape of the elements.

An FSS can be designed to function with a high-pass, low-pass, band stop or band pass filter response. The filtering response of a single layer series resonant FSS is known to suffer from narrow bandwidth for higher inductance and lower capacitance designs. However, the most common technique to increase the bandwidth and improve the filtering response is by cascading single layers with the inclusion of a dielectric spacer.

Munk authored a comprehensive and complete account of the history and design techniques of the classical FSS. The transmission and reflection characteristics of FSS can be dynamically tuned using a tuning circuit. The surfaces are made inductive or capacitive by adjusting the DC voltage...
applied to a varactor diode. These methods increase the size, cost and complexity of the design and require a large number of active elements.

Applications like selective frequency shielding of room windows in order to prevent the leakage of radio waves into and out of rooms, in train and aircraft windows isolating the unwanted radiation, conformal coating for conformal antenna radomes, have emerged in the past decade. It has increased the demand of a FSS on a dielectric which is optically transparent in the visible spectrum. Polycarbonate is one of the types of clear optical plastic with refractive index of 1.6 and wide range of temperature and chemical resistance. Polycarbonate used as a substrate in this analysis can provide both clarity and flexibility.

This paper presents a grid lattice array of silver screen printed rings on a thin polycarbonate substrate. The plastic substrate material is available in thin, flexible, highly transparent grades. The screen printing technology is an economical printing methodology with low cost set up and easy mass production. The structure of the ring resonator FSS has been studied previously but to the best of our knowledge, the research of ring resonator on a thin flexible optically transparent substrate is novel. The angular and polarization stability of the ring FSS over oblique angles makes them valuable for shielding applications where the angle of incidence is unknown. These polycarbonate films are biodegradable. Research so far shows large unit cell size used to design the FSS operating at lower frequency bands. But filtering capacities and applications for various smaller structures demand high density of FSS unit cells and small periodicity/unit cell size. In this paper an attempt is made to design an FSS on a thin dielectric material with low dielectric constant, without compromising the miniaturization of the unit cell. Section II of this paper discusses the physical specifications of a miniaturized ring resonator array which blocks the transmission at 12.5 GHz. To validate this concept, an FSS prototype was fabricated and measured. Further, subsequent sub sections of this paper investigate the influence of polarizations, change of wave incident angles, substrate permittivity and substrate thickness, on the stop band transmission performance and bandwidth of the array.

II. DESIGN AND MEASUREMENTS

A. FSS physical specifications

A uniform planar FSS structure was printed on plastic film. The ring resonator band stop elements of the array are electrically small fulfilling the rising demand of FSS miniaturization. The key features of these planar structures are (1) they are simple to manufacture since there are no shorting vias or pins (2) they have a low cost of manufacture in large quantities (3) they are compatible with standard planar printing technologies. The geometry of the elements in the FSS structure, rather than the periodic properties of the array largely determine the centre frequency and bandwidth of the stop band. This FSS structure consists of a lattice of metallic rings backed on a thin plastic substrate. The plastic substrate is a polycarbonate which is a long chain of linear polyesters of carbonic acid and dihydric phenols such as bisphenol A, also known by the trade name LEXAN. This clear and colourless heterochain polymer is used mainly for engineering and optical applications. The unique properties of polycarbonate include the impact strength, scratch resistance, easy moldability, high transparency to visible light leading to better transmission than many kinds of glass. The polycarbonate used in this analysis provides both clarity and the flexibility.

The array of circular ring resonators in a square lattice backed with plastic (polycarbonate) substrate with \( \varepsilon_r = 3.2 \) and thickness of 0.21 mm is shown in Figure 1(a). The solid ring denotes the presence of conductive material which is silver Electrodog 479SS, with ink conductivity of \( 43 \times 10^6 \) S/m. Because of its high conductivity, silver offers a superior performance with low cost compared to traditional techniques. However, the ring width has to be kept very thin in order to ensure the optical transparency, as the ink is opaque. The square frame depicts the unit cell of the FSS structure which is shown in Figure 1(b). The Table I shows the physical dimensions of the proposed FSS for stop band transmission performance.

The conducting ring introduces a self-inductance due to the flow of charge in the loop and also a mutual inductance due to the coupling with adjacent loops. Similarly, the charge distribution
across the small gap between the adjacent rings creates the substantial capacitance. The combination of these cascading capacitance and inductance structures produce a low impedance surface near its resonant frequency, producing the stop band region in which the plane wave transmission through the structure is blocked, and the magnitude of the reflection coefficient approaches unity. The Figure 1(c) gives the equivalent circuit model of the ring resonator array. The lumped LC model suggests that, decreasing the gap width $s$ between two adjacent rings increases the capacitance which in turn reduces the stop band frequency. An increase in the inner diameter of the ring decreases the track width of the ring, increasing the path for the flow of current and so increasing the inductance and decreasing the stop band frequency. These form the general design rules for frequency selective ring resonators.\(^5\)\(^,\)\(^9\) However, unlike coplanar concentric rings or square loops where the element to element spacing is uniform, the gap width $s$ associated with the proposed coplanar rings changes constantly with the changing ring curvature.

Furthermore, in order to avoid the scattering of energy in undesirable directions the spacing of the repeating element has to be less than the shortest wavelength for the broadside incident angle ($0^\circ$ incident angle) in the considered operating band. For large incident angles like $45^\circ$ the repeating element space should be half free space wavelength in order to avoid the wasted energy or grating lobes. This is a rule of thumb for designing an FSS. Following the general rule in this case the FSS elements are placed in a square lattice spacing obeying the formula given in Ref. \(^9\)

$$\frac{W}{\lambda} < \frac{1}{(1 + \sin\theta_0)}.$$  \hspace{1cm} (1)

For an incident angle ($\theta$) of $0^\circ$ this reveals $\frac{W}{\lambda}$ needs to be less than 0.327. Research done so far has shown smaller ring diameter ($d_1$) results in higher frequency and smaller unit cell size ($W$) ensures good frequency response with varying incident angles.\(^10\)

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Description</th>
<th>Dimensions(mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W$</td>
<td>Unit cell size</td>
<td>7.53</td>
</tr>
<tr>
<td>$d_1$</td>
<td>Out ring diameter</td>
<td>6.73</td>
</tr>
<tr>
<td>$b$</td>
<td>Thickness of ring</td>
<td>0.51</td>
</tr>
<tr>
<td>$s$</td>
<td>Spacing between rings</td>
<td>0.8</td>
</tr>
<tr>
<td>$t$</td>
<td>Track ink thickness</td>
<td>0.01</td>
</tr>
</tbody>
</table>
The performance was studied using CST Microwave studio which uses full wave methods to perform the analysis of the structures. The ring FSS array is assumed to be flat and infinite. The use of the unit cell boundary conditions in the directions of periodicity (x, y directions and fields expanded as a set of Floquet ports) allows a rapid and accurate simulation in CST Microwave studio. In the preliminary electromagnetic simulation, a circular FSS array printed on a thin polycarbonate film gave a fundamental resonance at 12.5 GHz which will be discussed in the next sections. This work is done at 12.5GHz and is scalable to lower frequency applications. Also the unit cell size of the basic 12.5GHz ring is appropriate for intended applications and further work is to be published which will lower the frequency while retaining the same unit cell size.

B. Fabrication process

Following the above specifications of the proposed FSS a prototype was fabricated using screen printing technology. The screen printing technology is characterized by few simple steps like 1) using silk stencil which defines the area to be printed 2) pushing ink through to make tracks on the dielectric substrate 3) drying of those tracks to make them conductive. The silver ink used to draw conductive tracks has a low level of environmental toxicity. The conductivity of silver ink paste is $43 \times 10^6$ S/m, the relative permeability $\mu_r$ is unity and the thickness of track is 10μm.

C. Bandstop transmission response

The frequency response of the proposed FSS surfaces was measured using two microwave horn antennas as shown in Figures 2(a) and 2(b). The measurement was performed in a microwave anechoic chamber. The two horns were placed at the same height from the ground facing each other, aimed at the surface under test. The transmitting antenna is placed 60cm from the FSS and the receiving antenna is placed 70cm from the FSS under test. The set-up is calibrated for reflection ($S_{11}$) and transmission ($S_{21}$). The reflection calibration is achieved by using a flat metal sheet with
FIG. 3. Experimentally measured and simulated transmission spectra of the FSS ring array on 0.2mm polycarbonate film for a normal incident plane wave over 2-18GHz.

difference observed is the maximum attenuation value, in which the simulated $S_{21}$ resonance presents a slightly higher attenuation value (−35.36dB) than the experimental one (−33.45dB). The temperature, humidity, air gap and misalignment are some of the factors which are not considered in a simulation configuration, thereby resulting in a slight difference in attenuation values. The next section focuses on the factors governing FSS response. These include support substrate permittivity, substrate thickness and signal incident angles.

1. Low polarization and angular insensitivity

The circular ring elements are less sensitive to incident angles when compared to many other differently shaped elements such as crossed dipoles, tripoles etc. The circular ring array is assumed to be a flat and infinite structure. The two floquet ports are set and the fields on either side of the circular rings are then expanded as a set of floquet modes exciting two plane waves with orthogonal electric fields (TE and TM modes). For normal incidence the well-defined stop band exists at 12.5 GHz frequency (Figure 3). A parameter sweep was carried out for the transmission response of the circular rings on 0.21mm thick substrate for oblique angles up to 60°.

The general features of the stop band stay the same as that for the normal incidence which shows a well-defined stop band at 12.5GHz. From Figure 4(a) for the TE mode, the higher order resonances (corresponding to higher angles) appear to remain at the resonant frequency. The drift
in stop band frequency is negligible, however the broadening of the stop band is observed especially for 90°. From Figure 4(b) the TM mode appears to move slightly farther from the resonant frequency. For TM incidence, resonant frequency shifts from 12.5GHz to 13GHz for higher angles from 30° to 90° resulting in a frequency shift of 3.3%. The explanation being as the angle of incident wave increases, for TM excitation the rings look flatter and the path for flow of current looks shorter, thereby causing the shift in resonant frequency.

2. Effect of change in substrate permittivity on resonance

In order to identify and verify the effect of the plastic substrate on the transmission characteristics, substrates with different permittivity were compared (see Figure 5). The FSS structure has the highest resonant frequency when air is the substrate material. As the permittivity of the substrate is increased, the stop band rejection frequency decreases. The resonant frequency is reduced from
FIG. 6. Plane wave transmission coefficient ($S_{21}$) for an un-printed plastic substrate for different thicknesses.

15 GHz (no substrate) to 12.5 GHz using a plastic backing of thickness 0.21 mm. A standard FR4 PCB of 1.6mm thickness backing sheet reduced the frequency to 11.84 GHz. Glass with similar thickness of 0.21mm but high dielectric constant of 10 reduced the frequency to 9.3GHz. Research done so far focuses more on use of high dielectric constant material in order to reduce the FSS cell size. In this paper, an attempt is made to use a low dielectric constant material without compromising the thickness of substrate and the millimeter unit cell size.

The unprinted plastic substrate under normal incident plane wave transmission was studied. It was found that when the substrate thickness becomes a significant part of a wavelength at the frequencies of interest, the reflection between the air and plastic interfaces creates a cyclic filter effect due to the standing waves generated in the plastic substrate. Figure 6 shows this effect for a change in substrate thickness ranging from 1mm to 12mm with step size of 4mm. As the substrate thickness increases the $S_{21}$ value cycles more rapidly versus frequency as expected.

3. Effect of change in substrate thickness on resonance and bandwidth

The FSS structures were printed on the plastic substrate. The parameterization of the FSS structure and the thickness of the substrate, up to certain values, controls the stop band frequency of the FSS structure. The bandwidth of the band gap can be altered by adjusting the thickness of the plastic substrate. The total filtering effect shows a direct relation with the thickness of the backing substrate (see Figure 7).

Figure 7 shows a reduction in the stop-band frequency as the substrate thickness is increased. For thin substrates around 0.2mm the stop band frequency changes rapidly as the thickness increases. As a result, it is possible to obtain significant frequency reduction by using quite thin polycarbonate sheet as the substrate. There is also little electrical advantage in using sheets greater than 1.8mm in thickness. Thicker sheets of course would give greater structural integrity but thinner sheets are flexible and can be used as conformal coatings and have greater optical transparency. Figure 7 shows the dependence of the -10dB bandwidth on substrate thickness ranging from 0 to 12mm. The bandwidth should decrease as the resonating frequency decreases but the use of thin plastic substrate reverses the effect at certain wavelengths letting the thickness control the bandwidth of the structure. The peaks in the bandwidth plot in Figure 7 result from the combined dielectric loading effect of the thickness.
FIG. 7. Effect of plastic substrate thickness on the stop band frequency and the 10 dB bandwidth for $\varepsilon_r = 3.2$.

of the plastic and the back reflections from the plastic for a given substrate thickness. The transmitted signal and the signal reflected within the plastic will arrive at the metal rings with varying phase difference depending on the frequency being transmitted. This means that as the frequency is varied, the impedance at the frequency selective surface changes. Analysis shows the impedance at the FSS surface, over the frequency range of 2-18GHz at constant thickness of plastic, shows the broadening and narrowing of the frequency curve near/at the quarter and half wavelength thicknesses of plastic substrate. Therefore, there is a tuning effect in which dielectric thickness can be used to control both the resonant frequency and the bandwidth of the band gap. Adjusting both the ring diameter or separation, and the substrate thickness can allow the design of an FSS material with the desired resonant frequency and bandwidth properties.

III. CONCLUSION

The comparative study of s-parameters of a ring FSS structure on a plastic (polycarbonate) dielectric substrate shows a good agreement between measured and simulated results, supporting the viability of polycarbonate film as backing substrate for printed FSS. From the $S_{21}$ measurements it is observed that as the substrate thickness is increased, the stop band rejection frequency decreases. It appears that for a substrate thickness above 1.8mm the resonant characteristics remains unaffected and so thick substrate can be replaced by thin film for the same frequency response. For example, 1.6mm thick FR4 PCB could be replaced with 0.4mm transparent polycarbonate sheet and maintain the same resonant frequency. Conversely, an even thinner sheet could be used with a higher frequency, or the structure could be enlarged to maintain the same frequency properties. The bandwidth of the FSS structure shows a cyclic effect due to the change in substrate thickness. Therefore, a wide band gap can be obtained even for thin plastic substrates. The thin flexible plastic substrate allows FSS structures to have a multitude of applications such as in scanned phase arrays, conformable shielding devices in GPS, in cockpit windows needing frequency selective properties and platforms for military vehicular antennas. The other applications include the selective shielding of frequencies. Various office environments make use of pico-cellular wireless communications such as personal handy phone system where in order to improve the efficiency each room needs to
prevent leakage of radio waves into and out of the room. The shielding of windows, floors and ceilings of each room by an FSS can overcome this problem. In\textsuperscript{12} a ring type frequency selective surface (FSS) provides transmission stop-band characteristics between rooms. This allows frequency reuse of one LAN by adjacent room with less attenuation. The investigations are made by placing the ring FSS on various target objects in the building industry. FSS windows can also be used in trains and aircrafts in order to isolate the unwanted radiations. As the silver paint rings on polycarbonate are printed using standard printing technologies, they have a low cost of manufacture compared to traditional PCB structures or other types of shielding glass. They can also be manufactured in very long continuous sheets which can be rolled for transportation. New technologies in laser modified conductive plastics may further improve the technology.\textsuperscript{13} However the next stage is to explore a new conformal mapping technique which would take into account the effects of ring curvature and the bending properties of these flexible FSSs, further applying them in conformal or non-uniform surfaces. The aim is to produce a device that can be designed for a target application.

APPENDIX 2
Miniaturised meandered square frequency selective surface on a thin flexible dielectric with selective transmission

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Flexible and Printed Electronics

PAPER

Miniaturised meandered square frequency selective surface on a thin flexible dielectric with selective transmission

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Keywords: frequency selective surfaces, flexible, meander square, single layer double sided FSS, GSM

Abstract

A low profile, thin, flexible dual layer frequency selective surface (FSS) operating in L-band has been designed and fabricated using screen printing technology. The composite FSS structure was achieved by meandering the basic $\lambda_o/22$ square loop at its four corners filling the space on the top layer and half period offset pattern on the bottom, which produces a reject band at 1.89 GHz. The frequency response of the FSS structure for both transverse electric and transverse magnetic polarisations and various angles of incidence using measured and simulated results for single as well as double sided FSS show good agreement. The main purpose of this paper is to propose a design applicable for FSS windows with selective transmission and shielding at frequencies such as mobile communication signals (GSM) working around 1.89 GHz.

1. Introduction

For the past few years frequency selective surfaces (FSSs) have received significant attention due to their ability to control the propagation of electromagnetic waves across boundaries. FSSs have been widely used in the design of spatial filters, microwave absorbers, dichroic sub reflectors, artificial electromagnetic band gap materials and antenna radomes. FSSs have enhanced the signal-to-noise ratio, the bandwidth and the channel capacity of communication channels of satellite platforms [1]. Besides their many applications at microwave frequencies, their use at cellular mobile bands is new. The reason being the requirement for them to resonate at cellular bands [2].

A typical FSS is a 2D planar structure with periodically arranged metallic elements, backed by a dielectric substrate. These structures can either block or pass electromagnetic waves of a certain frequency depending upon the specific shape of the conducting elements [3]. Much attention has been paid to designs which provide stable spectral responses for normal and off normal angles of incidence. In traditional FSSs, the desired transmission results from the mutual coupling between the large numbers of unit cells for which the overall size of surfaces must be electrically large. For applications at low frequency where small screens of relatively small electrical dimensions are desirable, the unit cell size needs to be minimised without compromising the angular stability [4]. To address this problem, more resonant lengths are meandered and packed into the unit cell. The concept of meandering the array element not only reduces the unit cell size but also ensures a stable stop band (in case of loop type FSS) responses over the oblique angles of incidence and isolates the fundamental resonance from the grating lobes [5]. In a traditional single layer FSS tight tolerance conditions are required unless the resonant element dimension is made a small fraction of the operating wavelength, as indeed is seen the case of novel convoluted elements [5]. Single layer band pass spiral FSS structures with miniaturised unit cell of $0.058\lambda_o$ [6] and $0.061\lambda_o$ in dimensions, were developed in [7]. The miniaturised characteristics were stable with respect to the different polarisations and incident angles. The only drawback associated with these FSS structures was the use of thick substrate.

The approach of miniaturising the unit cell was extended in designing double sided FSSs. The miniaturised element comprised a metallic loop and a wire grid printed on either side of a Duroid substrate, with a unit cell size of $0.083\lambda_o$. The meandered tracks in a unit cell act as lumped inductive and capacitive elements which can be placed in order to couple the magnetic and electric fields of an incident plane wave,
respectively, to achieve band-pass behaviour, as shown in [8]. A new miniaturised double sided FSS comprising micro-wire resonating elements with unit cell size 0.067λo was also presented in [9]. The structure demonstrates a better stability over wide angles of incidence and different polarisations. However, in these studies, the FR4 or Roger RT/Duroid was selected as substrate; which is mechanically not flexible. Such structures are not useful for shielding applications which involve conformal surfaces.

In this paper, we present a miniaturised dual layer FSS screen printed on each side of a thin flexible dielectric substrate. The FSS exhibits –10 dB stop bandwidth of 2.14 GHz ranging from 1.20 to 3.34 GHz. The objective of this work is to design a thin FSS-based wall configuration which can provide frequency shielding at GSM bands (e.g. DS1800 used for mobile communications). The analysis involves meandering the square loop at four corners and then offsetting one of the layers to provide maximum coupling between the resonant elements. These techniques have proven to help in miniaturisation of the structure and in frequency tuning. The dimensions of the FSS elements are much smaller (λo/22) than the operating wavelength. Section 2 represents the geometry and basic design specifications of FSS and the corresponding equivalent circuit model. Section 3 discusses the effect of meandering the FSS element on the overall performance and the various offset techniques used to enhance the bandwidth. The screen printed prototype measurements are presented in section 4. For both single and dual layer FSS, the measured and simulated results are in good agreement. Two FSS screens are cascaded in order to improve the bandwidth and the effect of separation between the two screens is also presented. The features of the structure include the flexible nature, compact unit cell size, stable frequency and polarisation response over the wide variation of angle incidence. The screen printing technology has made it possible to cheaply manufacture frequency selective shields for room walls and windows which can allow/block specific frequency bands.

2. FSS specifications

2.1. Basic design

The elemental FSS consists of two screen printed inductive layers on a thin flexible dielectric substrate, as shown in figure 1. The square loop element was chosen as the basic model to build the final FSS structure because of its good performance in the microwave frequency spectrum [10].

The loop on the top layer contributes to the inductance and the gap in between the adjacent loops provides the capacitance, therefore acting as a series LC resonator. The transmission is blocked at its resonant frequency and the sheet impedance is zero making it a perfect reflector, thus the structure behaves as a stop band filtering screen for both x and y polarisations.
The two metallic layers are separated by a thin flexible polycarbonate film with a relative permittivity of \( \varepsilon_r = 3.2 \), a loss tangent of 0.0025 and a thickness of \( h = 0.21 \) mm. The dimensions of the structure are listed below in table 1.

The equivalent circuit shown in figure 1 with both FSS layers is modelled as a series LC resonator. The two FSS layers are separated by a thin dielectric substrate represented as a short transmission line whose length is the electrical thickness of the substrate \([11]\). The characteristic impedance of the substrate is \( Z_s = Z_0 / \sqrt{\varepsilon_r} \), where \( \varepsilon_r \) is the dielectric constant, \( \ell \) is the length and the free space impedance \( Z_0 = 377 \) \( \Omega \). As the thickness of the substrate is relatively small, its equivalent circuit transmission line can be neglected, thereby the FSS structure can act as a lumped element model with two serially arranged LC resonators \([12]\).

The mutual coupling between the layers is modelled as the mutual inductance and mutual capacitance. The coupling coefficient between the two layers controls the centre frequency and bandwidth of the FSS structure \([13]\). The transmission characteristics were modelled using CST microwave studio, with full wave methods of simulation. The unit cell boundary conditions were set in the directions of periodicity and the fields are expanded as a set of Floquet modes.

### 3. Optimising the structure

#### 3.1. Meandered structure

The structure was optimised manually to miniaturise the element while tracking the band reject frequency. The conducting element of the basic square model was meandered at the four corners in two stages as shown in figure 2. Meandering reduces the electrical size of the FSS and can greatly improve the overall performance of FSS.
By modifying the element, the equivalent inductance increases and the gap between the proximal elements filling the space increases the capacitive coupling. Figure 3 compares their transmission coefficient for a single sided FSS. As the number of meander curves is increased the central frequency for the stop band decreases from 8.7 to 5.4 GHz. The $-10$ dB stop bandwidth shows a drop from 30.7% to 20% as the element gets meandered.

The bandwidth of the FSS can be controlled by increasing the number of meanders ($n$) in the element, as seen in Table 2. The single sided structure (see figures 2(b) and (c)) can operate at a low frequency

<table>
<thead>
<tr>
<th>Stages</th>
<th>No. meanders ($n$)</th>
<th>Track length ($L_2$)</th>
<th>Res. Freq ($f_r$)</th>
<th>Bandwidth (BW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basic model</td>
<td>0</td>
<td>$0.23\lambda$</td>
<td>8.7 GHz</td>
<td>3.2 GHz</td>
</tr>
<tr>
<td>1st convo. stage</td>
<td>4</td>
<td>$0.16\lambda$</td>
<td>6.06 GHz</td>
<td>1.4 GHz</td>
</tr>
<tr>
<td>2nd convo. stage</td>
<td>12</td>
<td>$0.14\lambda$</td>
<td>5.4 GHz</td>
<td>1.2 GHz</td>
</tr>
</tbody>
</table>

Note: $\lambda$ is the resonant wavelength of each FSS as defined by the resonant frequency.

Figure 4. The layout of the bottom side element with meanders. (a) same shape zero displacement, $n = 12$ (b) same shape half period displacement in $x$ and $y$ axis, $\Delta x = 0.5L_3$, $\Delta y = 0.5L_3$, $n = 12$ (c) same shape half period displacement in $x$ and $y$ axis, $\Delta x = 0.5L_3$, $\Delta y = 0.5L_3$, $n = 16$ (d) overview of the FSS structure with an offset in the bottom layer.

Table 3. Normal incidence response for various offset bottom surface configurations.

<table>
<thead>
<tr>
<th>Configurations</th>
<th>Offset values</th>
<th>$f_r$(GHz)</th>
<th>$-10$ dB BW(GHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SS, $n = 12$</td>
<td>0, 0</td>
<td>5.40 GHz</td>
<td>1.20 GHz</td>
</tr>
<tr>
<td>DS same shape, $n = 12$</td>
<td>0.5$L_3$, 0.5$L_3$</td>
<td>5.98 GHz</td>
<td>1.94 GHz</td>
</tr>
<tr>
<td>DS same shape, $n = 16$</td>
<td>0.5$L_3$, 0.5$L_3$</td>
<td>1.89 GHz</td>
<td>2.14 GHz</td>
</tr>
</tbody>
</table>

Note: SS—single sided; DS—double sided; $n$—number of meanders.
with the same unit cell size. Moreover, in order to design a basic square loop which can resonate at 5.4 GHz, the element unit cell size needs to be 10.6 mm. So an area reduction of 53.86% was achieved by meandering the element. The overall FSS structure was further modified by screen printing the proposed FSS (figure 2(c)) on the reverse of the dielectric substrate. When a linearly polarised plane wave impinges upon the structure, positive and negative charges are accumulated on the top and bottom sides respectively, creating the additional mutual capacitance, $M_t$ and mutual inductance, $M_i$ between the two surfaces. The combination therefore acts as a parallel combination of two series LC resonators, having stop band characteristics.

3.2. Layer offset (only bottom surface)

The filtering response of a single layer FSS is known to suffer from a narrow bandwidth because of high inductance and low capacitance designs. The most common technique to increase the bandwidth and improve the filtering response is by increasing the number of FSS layers with the inclusion of a dielectric spacer [14]. From [12] and [13], it is seen that various offset techniques can be used to change the coupling coefficients and the bandwidth of a double layer FSS. In order to study the various offset techniques, three configurations were considered in which elements on both sides of dielectric had:

1. The same shape aligned with no offset on bottom surface and meanders, $n = 12$.
2. The same shape with both axes offset by a half period on bottom surface and meanders, $n = 12$.
3. The same shape with both axes offset by a half period on bottom surface and meanders, $n = 16$.

For all cases, figure 2(c) serves as the top side FSS element and the bottom side is shifted in both along x and y axes simultaneously, as shown in figures 4(b) and (c). The relative lateral displacement in dual layer FSS has proven to be important in electromagnetic design as it affects the mutual inductance and capacitance of the conducting elements [13].

The offset changes influence the inductance and capacitance values which give rise to different coupling coefficients and bandwidths. It is important to appreciate the significance of the number of meanders introduced in the square loop and their area of overlap between the two sides of FSS. The analysis shows that the shape from figure 4(c) in which the number of meanders is $n = 16$, has a lower stop band and a broader bandwidth as compared to the other configurations. The reason being the lumped inductor and lumped capacitor in the double sided FSS are placed in a manner that maximum coupling to the electric and magnetic field of the incident plane wave is achieved. The results are tabulated in table 3.

4. Experimental validation

4.1. Prototype and measurement set up

Following the physical specifications mentioned in table 1, the double sided meandered FSS was fabricated and measured for its validity. The miniaturised FSS was manufactured using the screen printing technology. The conductive elements were printed on the substrate using a silver ink with conductivity of $43 \times 10^6$ S m$^{-1}$ and thickness of 10 $\mu$m. The prototype sheet was 23 cm $\times$ 28 cm in size and consists of $28 \times 35$ number of elements fabricated on 0.21 mm (210 $\mu$m) thick dielectric substrate with permittivity of 3.2 and loss tangent of 0.0025, as shown in figure 5.

Besides the miniaturised nature of the designed FSS and the packing of resonant lengths in the given area of small unit cell, the screen printing technology provides high precision and resolution. The measurement was carried out in a free space in a microwave anechoic chamber. Free space testing is the common method for measuring the permittivity and permeability of the materials. Standard horn antennas were placed 60 cm from the sample, each connected to a vector network analyser interfaced for S-parameters
measurements. The schematic diagram and the actual experiment set up is shown in figure 6.

The measurement was performed in two steps: (a) calibration was achieved by eliminating the losses in the cable and foam by measuring the S11 and S21 between the two horns without the sample. (b) The diffraction around the metal with the same size as the sample subtracted from subsequent sample measurements was measured.

4.2. Transmission response at normal and oblique angles

The FSS is assumed to be an infinite periodic flat structure with a unit cell boundary conditions in the x, y directions and fields expanded as a set of Floquet modes. The unit cell was excited by an incident plane wave with different polarisations and different angles of incidence. The stop band for the double sided FSS is well-defined at 1.8 GHz in both simulated and measured results as shown in figure 7. There is some difference in the insertion losses which might be because of air gap, misalignment, dielectric loss, calibration accuracy and measurement tolerances at such a relatively low frequency band.

When the electric field is perpendicular to the plane of incidence, the polarisation is termed as transverse electric (TE) polarisation and when it is parallel to the plane of incidence the polarisation is termed as transverse magnetic (TM) polarisation [15]. The sensitivity of the frequency response of the single sided and double sided FSS prototype was also measured at incident angles ranging from 15° to 60° for both TE and TM polarisations. These measurements were made over a frequency range of 1–12 GHz. It is evident from figure 8(a) that for the single sided FSS with TE polarisation a wider band performance is achieved and the frequency shift is <6.7%. However, for TM polarisation the band edges are nearly the same as those of the normal incidence with a frequency shift of <3%. As evident in figure 8(c), the centre frequency of operation of the double sided FSS does not significantly change (<2%) as the angle of incidence is increased from 0° to 60° for TE polarised plane waves. However,
as the angle of incidence changes, the bandwidth gets wider. The ripples in the response curves beyond 8 GHz are due to the multipath fading caused in the testing environment. For TM polarisation, the transmission response for higher angles starts to drift slightly (<6.4%) beyond the centre frequency, obtained at $\theta = 0^\circ$. There is little effect on the bandwidth and the band edges. Despite the difference in insertion losses which can be due to dielectric and conductive losses, a good match is obtained between the simulated and measured results in this experiment for the double sided FSS. It further verifies the stable behaviour of this miniaturised low profile FSS.

4.3. Cascaded FSSs to improve the bandwidth

It is usually the biggest challenge to design band stop filters with large bandwidth [1]. The designed double sided FSS is a low profile shielding surface with stable angular properties. A considerable bandwidth was

Figure 7. Transmission and reflection response for the double sided FSS with two axis offset, at normal plane wave incidence.

![Figure 7](image)

Figure 8. Comparison of measured and simulated frequency selective characteristics at normal and oblique angles (a) single sided FSS TE polarisation (b) single sided FSS TM polarisation (c) double sided FSS TE polarisation (d) double sided FSS TM polarisation.

![Figure 8](image)
achieved by placing two FSS arrays in free space positioned in parallel planes.

The simulated transmission coefficient for a single layer FSS compared with the cascaded FSS is shown in figure 9(a). As can be seen the band stop frequency for the different cases remains well centred at 1.89 GHz. However, the sharpness of the transmission curve is improved by cascading the two FSSs. The lower limit frequency \( f_L \) of the transmission curve shifted slightly whereas the upper limit frequency \( f_H \) exceeds the single layer value from 3.34 to 6.18 GHz, providing a broader \(-10 \, \text{dB} \) bandwidth (55.6%) compared to the non-cascaded FSS. The two identical double sided FSS arrays separated by 0.04\( \lambda \), corresponding to 7 mm could be most applicable to improve the shielding of cellular communication signals through glass or perspex windows of appropriate thickness. The bandwidth analysis was performed over larger separations between the two double sided FSS ranging from 2 mm (\( \sim 0.01 \lambda \)) to 80 mm (\( \sim 0.5 \lambda \)) as shown in figure 9(b). There is a cyclic effect in bandwidth over the thickness which can be caused due to the multi layering of FSSs and the standing wave generated by the electromagnetic fields in the separation region coupling the energy from one FSS to the other. Figure 9(c) shows the generalized portrayal of the cascaded configuration in which the designed double sided single layer FSS was spaced from an identical corresponding FSS. Further, for the broadband applications with less structural or space constraints more FSS screens can be cascaded in a multilayer arrangement at predetermined spacing or filled with appropriate dielectrics to widen the band stop regions.

**Figure 9.** (a) Transmission curves for normal angle of incidence for single layer double sided (SLDS) FSS and cascaded FSS with array separations, \( D_x = 2 \, \text{mm} (\sim 0.01 \lambda), 5 \, \text{mm} (\sim 0.02 \lambda), 7 \, \text{mm} (\sim 0.04 \lambda), 10 \, \text{mm} (\sim 0.06 \lambda) \) respectively where \( \lambda \) is the resonant wavelength. The gap between the two FSS screens are filled with free space, dielectric constant, \( \varepsilon_r = 1 \). (b) Bandwidth variation over a range of separation between the two FSS arrays. (c) Layout of cascaded configuration.
5. Conclusion

This paper describes a FSSs implemented on two sides of a single layer substrate using screen printing technology with a stop band intended to shield cellular frequencies. In comparison to the references [4–9], a significant reduction in stop band frequency (1.89 GHz) has been achieved by the proposed miniaturised FSS. The unit cell size of the proposed FSS, $0.045 \lambda \times 0.045 \lambda$, has been significantly reduced in comparison to this earlier work. The basic square loop was optimised by meandering the sides and then offsetting the bottom surface FSS on the dielectric substrate in a manner that the element tracks superimpose and the structure behaves like a lumped element model increasing the mutual coupling. Experimental results are in good agreement with the simulations, thereby validating the design concept for GSM applications in radomes and other microwave systems. The success of the design emanates from the maximum coupling achieved by offset techniques. The sensitivity of the response of the designed FSS to the normal and oblique angle of incidence, and to both TE and TM linear wave polarisations, was analysed. Apart from the miniaturised element, reduced resonant frequency and the angular stability up to 60°, the −10 dB bandwidth of the proposed FSS structure can be controlled and extended out to 1.20–3.34 GHz and can be further enhanced by cascading the two identical FSSs without changing the stop band frequency. By virtue of its flexible nature, low manufacturing cost and easy mass production, the designed conductive FSS can be rolled into long continuous sheets or wall papers and used in frequency shielding over wall/window configurations or both. It is also applicable for shielding conformal surfaces.

References

Screen printed frequency selective surfaces for room isolation in buildings

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Abstract—A ring type frequency selective surface (FSS) can provide transmission stop-band characteristics in rooms. This allows adjacent rooms to be isolated for one LAN for frequency reuse while other frequencies pass through the walls with minimal attenuation. The FSS was screen printed on a thin flexible plastic substrate of permittivity 3.2 with a stop band at 12.3GHz and 10dB bandwidth of 3.5GHz. The variation in bandstop characteristics was investigated for various wall materials. The centre frequency varied by more than 3 GHz for common wall materials which means significant transparency for some building materials. The technique is a low cost method of confining LAN picocells in one room.

Keywords — printed FSS; ring FSS; FSS on target object; band-reject FSS, picocellular networks, transmission through walls;

I. INTRODUCTION

The number of wireless networks continues to increase with time. In buildings, picocellular communications, wireless sensor networks (WSN) and mobile telephone bands must co-exist. While operating at very different frequencies, the challenge remains to ensure good connectivity for large area networks and well defined spatial limits for picocellular networks and WSN. There is also some interest in room isolation for data security. Frequency reuse and network security are two drivers to ensuring picocell isolation. A coating of metamaterial [1] is one option available to solve this problem, however the fabrication and installation costs must be very low to be economically viable [2]. As building materials include wood, paper (in plaster board), concrete and glass, a general purpose FSS which has similar isolation properties when placed against all of these materials is of interest.

The FSS is one type of metamaterial, a technique which employs a combination of dielectric materials and a regular array of sub-wavelength conductive objects. Such structures can be designed for band-reject transmission of microwave signals and is suitable for picocell isolation [3]. In the case of room isolation for a picocell, the bandstop frequency is most important. The ability to print conductors on a low cost, flexible plastic sheet means that installation on the walls and ceiling is relatively simple, and might even be incorporated into the wall materials themselves [4]. For example, prefabricated wall paneling could include the FSS structure without a significant increase in weight, volume or utility.

This paper discusses a printed FSS for picocell isolation inside a room. As the structure has no ground plane, the centre frequency of the stop band can be influenced by the electromagnetic properties of the wall materials the thickness of the wall. The effects on the FSS centre frequency was investigated for different target objects. The permittivity range of $1 < \varepsilon_r < 10$ and different thickness, $d$, are reported. While FSS characteristics have been reported previously, these studies have not commented on the FSS frequency changes with different wall materials.

The effect of various objects on the resonant frequency of printed RFID antennas has been reported [5], however, no simple calculation method exists to predict the change in resonant frequency. For this reason a full 3D electromagnetic modeling tool was required.

II. FSS DESIGN

The FSS used in this analysis is a conductive ring type. The rectangular array of rings was silver printed on top of substrate. This acts as a band stop filter. Figure 1 shows the dimension of the unit cell. The ring has width, $w = 0.26$ mm and radius, $r = 3.1$ mm on flexible a thin plastic substrate of $\varepsilon_r = 3.2$ with substrate thickness of 0.21 mm. The structure was modeled in 3D electromagnetic software using a plane wave source excited normal to the plane of the conducting ring. The transmission properties were evaluated as a function of frequency of the incident radiation. Parker et al found that circular ring elements are less sensitive to incident angles when compared to other differently shaped elements [6]. On varying the angle of incidence from 0° to 50° the general features of the stop band stay the same as that for normal incidence. However for the TE mode transmission the higher order resonances start moving closer to resonant frequency whereas for TM mode transmission higher order resonances start moving away from the resonant frequency.

The transmission characteristics of the structure in air (i.e. setting the target object properties to those of air $\varepsilon_r = 1$ and the conductivity $\sigma = 0$), are plotted in Figure 2 as a function of frequency. The 10dB bandwidth is 10.5GHz to 14.2 GHz and is approximately symmetrical about the centre frequency at 12.35 GHz. This bandstop frequency changes with the substrate relative permittivity $\varepsilon_r$. Clearly if the properties of substrate and the object are both known, the structure can be optimized for a required frequency. In many cases, however,
the electromagnetic properties of the object are not known, and can vary across the structure due to the addition of supporting beams and wall coatings.

When the FSS on a very thin substrate is placed on an object, the stopband frequency will change due to the different values of $\varepsilon_r$. The variation in the stopband frequency is shown in Figure 3 as a function of $\varepsilon_r$. The frequency decreases monotonically as the relative permittivity increases. For $\varepsilon_r > 4$, the frequency shift is greater than the original bandwidth of the structure. This change is similar to the change in resonant frequency of a planar dipole antenna on a very thin substrate [7].

The analysis was extended to observe the effect a changing thickness $d$ of the target object. Figure 4 shows the variation in the stopband frequency with object thickness $d$. This range was designed to include most common materials used in wall, door and window construction. Thus the target object thickness $d$ was increased in $d$ from 1mm to 20mm for wood, concrete wall, glass and paper. The results shows there is no significant change in frequency shift when the $d$ changes. Note that the quantization in the frequency axis is the result of a computational accuracy in frequency of 0.1 GHz.

![Diagram](image-url)

**Fig. 1.** Unit cell of the FSS structure consisting of a printed silver ring on top of a thin flexible plastic substrate and backed by target object.

**Fig. 2.** FSS transmission coefficient on a substrate with $\varepsilon_r = 1$ and thickness 0.21 mm. The 10 dB bandwidth is approximately 3.5 GHz.

**Fig. 3.** Change in the bandstop frequency of a printed circular ring FSS on a thin plastic substrate (thickness 0.21 mm) when the sheet is placed against a target object of thickness 2 mm with varying relative permittivity.

The very minor change in the FSS stopband frequency for $d > 1$ mm demonstrates that the thickness of the object is not an important parameter in the attenuation of the signal. Clearly the effect of the thickness on the capacitance between the rings is minimal.

**Fig. 4.** FSS stopband frequency variations on different objects: wood ($\varepsilon_r = 4$), concrete ($\varepsilon_r = 6$), paper ($\varepsilon_r = 8$) and glass ($\varepsilon_r = 10$) [8,9] as a function of the thickness.

As the thickness of target object has no significant effect on the FSS stopband frequency, the effect is only dominated by the change in relative permittivity.

Figure 5 shows the transmission coefficient of the FSS on substrate with and without the target object. The FSS without target object is similar to Figure 2 and has a 3.5 GHz...
bandwidth. With an object with $\varepsilon_r=10$ the bandwidth decreases to 2.5 GHz. Figure 5 clear demonstrates that the change is the centre frequency of the stopband is well outside the bandwidth of the FSS in air only. This is of significant importance in room isolation technologies. The printed FSS sheets designed for use on wood and concrete will not function satisfactorily when placed on glass.

The continuous line is the free space characteristic. The materials without the FSS coating show very little change with frequency. The FSS coating on wood (thickness = 20mm) and glass (thickness = 10mm) compared to the wood and glass alone.

Fig. 6. S21 experimental results showing effect of the FSS on wood (thickness =10 (o). The bandwidth is reduced by approximately 1GHz. This plot demonstrates that this FSS can not be used effectively on these two different materials.

The transmission coefficient (S21) was measured using two X-band pyramidal horn antennas placed 30cm apart facing each other and 14.5cm from the ground. The sample materials were placed halfway between the two horns and the response was measured as a function of frequency. The system was first calibrated using a free space path. The maximum generator frequency was 11.2 GHz and the sensitivity of the receiver was -35 dBm. Figure 6 shows that the attenuation (S21) characteristics when the thin plastic FSS was placed on wood and on glass. The measured free space path loss is the function of frequency. The S21 transmission characteristics for FSS on two different materials (wood and glass) were calculated by subtracting the free space variation (Wood FSS-Foam Plastic) and so is the glass with FSS (Glass FSS-Foam Plastic). The wood without the FSS was found to be frequency independent and has a mean absorption loss of -2.03dB. The loss through glass was also frequency independent and has a mean loss of 0.58dB. While the frequency range of the equipment was limited to below the stopband frequency, a statistical t-test was used to assess the difference between the two data sets. The results generated by this test are pooled variance, an accumulated measure of the spread of data about the mean, which is derived from this formula:

$$S^2 = \frac{n_1S_1^2 + n_2S_2^2}{n_1 + n_2 - 2}$$

where $n_1$ and $n_2$ are the number of observations for wood with the FSS and glass with the FSS respectively. The $S_1$ and $S_2$ are the mean values for the wood and glass respectively. The results showed that there is 80% level of significance to support the fact that the mean test values of two target objects are different. However, it is clear that the stop band center frequency is greater than 11.2GHz for both wood and glass materials, but the shape of the curve is convincing that there is a clear stop band for both materials resulting from the FSS.

CONCLUSION

This paper demonstrates the impact of a low cost, FSS created by printing silver on a thin, flexible, plastic substrate and placed on various target objects used in the building industry. The relative permittivity of the target object can have a large and significant impact on the FSS bandstop centre frequency. The thickness of the target object showed little effect on the bandstop resonance. The bandwidth is reduced with increasing values of $\varepsilon_r$, particularly on high $\varepsilon_r$ objects. This work demonstrates that the printed FSS can provide good isolation in a room if the object is designed for and placed on one particular type of building material. When there are a number of different object materials, then the bandwidth might be too narrow to accommodate the large variations in the centre stopband frequency. This means that there will be significant microwave transmission through the windows (for example). There are two possible strategies to overcome this problem:

a) The FSS needs to be constructed in such a manner that the bandwidth is increased. This can be achieved using differently sized FSS conductive rings on the same substrate. This needs further investigation.

b) The FSS needs to be designed specifically for the objects. Thus a prefabricated wall will have one geometrical structure and the windows must have another. The wall FSS will have a different stopband characteristic in free space compared to the glass FSS. When these FSS coatings are applied to the different materials enclosing the room, the stopband frequency is the same.
Note that the printed FSS has very good optical transparency so the windows remain quite transparent. The size and thickness of the conductive tracks is similar to the effect of insect screens commonly used in buildings.

REFERENCES


Transmission Bandwidth Enhancement Using Lateral Displacement in a Thin Flexible Single Layer Double Sided FSS.

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Abstract—A novel low profile frequency selective surfaces (FSS) with wide stop band characteristics suitable for UWB applications consists of square loops screen printed on both sides of a thin flexible polycarbonate substrate with a lateral offset in both directions. The design provides a -10dB insertion bandwidth of 4.55 - 12.77GHz. The design delivers stop band for angular incidence in both single sided and double sided configurations up to 60° degrees. The symmetrical nature ensures identical response for TE and TM modes of polarization within 30° incidence. A comprehensive iterative analysis was made to enhance the ultra-wide bandwidth.

Keywords—Frequency selective surfaces; lateral displacement; ultra-wide band; bandwidth enhancement.

I. INTRODUCTION

Frequency selective surfaces are planar periodic structures arranged in a one or two dimensional lattice printed on a dielectric substrate. The frequency selective surface can filter electromagnetic energy i.e. transparent to electromagnetic waves at certain frequencies and reflective/absorptive at others. Frequency selective surfaces have found enormous applications in microwave and optical systems. These periodic structures have been used as polarizers, filters, sub reflectors, radomes in order to control the radar cross section of the antenna configuration [1]. Some FSSs also offer the advantages of flexibility, optical transparency, thinness and enhanced bandwidth [2]. Different element geometries and dielectric substrates can enhance the bandwidth of an antenna system. The gain of the ultra-wideband antenna can be improved using a multilayer FSS [3] and in [4] the authors have introduced a wideband FSS by combining different resonating elements. However the stacked multilayers make the structure thicker, less mechanically flexible and less transparent. Fractals known for unit cell size reduction have been used for multiband FSS [5]. Comparatively large bandwidths have been achieved in intricate fractal designs, maintaining the compact FSS unit cell size [6]. From a design perspective, many other complex structures with different specifications have been used to improve the bandwidth including magnetic absorbers [7], space filling curves [8] and high impedance surfaces [9]. In all cases, the filtering capacity is improved whereas the shielding bandwidth is narrow. In order to address the issue of design complexity, a simple compact size FSS is desired which can ensure the performance with varying angles of incidence and can provide an ultra-wide stop band.

This paper presents a double sided FSS that exhibits a -10 dB stop bandwidth of 8.22GHz ranging from 4.55 - 12.77GHz. We propose a single layer FSS printed on each side of a thin flexible dielectric substrate. The FSS elements are an array of square loops on the top side and an identical array displaced on the bottom side of the dielectric substrate. The displacement changes the resonant frequency of the metallic loops and the bandwidth can be increased two fold. The dimensions of the FSS elements are much smaller (λ/5) than the operating wavelength. Section II represents the FSS geometry, design specifications and the various offset techniques used for bandwidth enhancement. The transmission response and angular stability of the FSS structure are discussed in section III. Various parameters and their effect on the FSS performance are dealt with in section IV. The FSS design has the advantages of a less complex structure, enhanced bandwidth due to half period displacements in the two directions, angular stability, polarization insensitivity and easy mass production in sheets.

II. FSS DESIGN AND SPECIFICATIONS

Fig. 1. shows the layout and the respective cross section of the basic model. The FSS structure consists of two printed metallic layers on both sides of the dielectric substrate. The pattern consists of a regular array of square loops and the supporting dielectric substrate is a flexible thin transparent film of polycarbonate, with relative permittivity 3.2, loss tangent 0.0025 and thickness, h = 0.21mm.

Fig. 1. Double sided Square Loop Stop band FSS unit cell. (a) FSS- Top side. (b) FSS- Bottom side. c) Equivalent circuit showing inductance and capacitance associated with the double sided square loop. (d) Cross-sectional side view from x-z plane.
In modelling investigation the FSS structure is assumed to be an infinite periodic structure. The FSS is illuminated by a plane wave, with electric field vector $E$ oriented in $y$ direction and the magnetic field vector $H$ oriented in $x$-direction. The FSS structure behaves like a series LC resonator where the loop contributes to inductance and the gap in between the two adjacent elements provides the capacitance [2]. The mutual coupling between the two sides is modelled as mutual inductance and capacitance. Since the thickness of the substrate is small, its equivalent transmission line length can be neglected. Therefore, the equivalent circuit is simplified as a parallel circuit of top series (FSS1) and bottom series (FSS2) LC resonators (Fig.1). The values of mutual capacitance, $M_c$ and mutual inductance, $M_l$ depend on the overlap of the metallic tracks and will vary in different configurations. The transmission is blocked by this FSS structure at its resonant frequency, therefore behaving as a stop band filter. The performance of the FSS was calculated using CST microwave studio, which uses full wave methods of simulation. The unit cell boundary conditions are set in the directions of periodicity.

### A. FSS Layer Offset

The enhancement of bandwidth is achieved due to lateral displacement of the bottom side relative to the top. The relative lateral displacement is important in the electromagnetic design as it involves a change in the mutual inductance and capacitance of the conducting elements. In this paper, various offset techniques were used to implement shifts in the stopband frequency while maintaining the compactness of the unit cell. In the numerical model the top side was fixed and the bottom was shifted in $x$ and $y$ direction as shown in Fig. 2 and 3.

![Fig. 2. Double sided square loop stop band FSS unit cell with half period displacement in $x$- or $y$- axis. (a) FSS top side. (b) FSS bottom side- displaced in $x$-direction. (c) FSS bottom side- displaced in $y$-direction. (d) Cross sectional view from $x$-$z$ plane, $\delta_x = 0.5L_1$. (e) Cross sectional side view from $y$-$z$ plane, $\delta_y = 0.5L_1$.](image)

Shifting the square loop on the bottom side of the dielectric by a half cell in $x$-axis ($\delta x = 0.5L_1$) or in $y$-axis ($\delta y = 0.5L_1$) does not affect the centre frequency of the stop band. However, the displacement parallel to incident E field (Y) leads to a slightly broader bandwidth as compared to the displacement parallel to the magnetic field (X). The half period offset was made in both $x$ and $y$ axes simultaneously, i.e. $\delta x = \delta y = 0.5L_1$ as shown in Fig. 3. Such an offset showed a wider bandwidth due to the increase in mutual inductance $M_l$ and the mutual capacitance, $M_c$ as compared to the other FSS configurations. The reason being that the lumped inductor and capacitor are placed in a way that they can have maximum coupling to the electric and magnetic field of the incident plane wave.

![Fig. 3. Double sided square loop stop band FSS unit cell with half period displacement in $x$ and $y$ axis. (a) FSS top side. (b) FSS bottom side- displaced in $x$- and $y$- direction (d) Cross sectional side view from $y$-$z$ plane, $\delta_x = 0.5L_1$ and $\delta_y = 0.5L_1$.](image)

The dimensions of the structure used in this investigation are given in the Table 1.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Description</th>
<th>Dimensions(mm)</th>
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<tr>
<td>$L_1$</td>
<td>Unit cell size</td>
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</tr>
<tr>
<td>$L_2$</td>
<td>Outer Sq. loop length</td>
<td>7.20</td>
</tr>
<tr>
<td>$t$</td>
<td>Thickness of track</td>
<td>0.01</td>
</tr>
<tr>
<td>$s$</td>
<td>Spacing in between loops</td>
<td>0.80</td>
</tr>
<tr>
<td>$w$</td>
<td>Width of Track</td>
<td>0.30</td>
</tr>
<tr>
<td>$h$</td>
<td>Thickness of Substrate</td>
<td>0.21</td>
</tr>
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</table>

### III. TRANSMISSION CHARACTERISTICS

#### A. Normal Incidence

The transmission response of the double sided FSS structure with the layer offset at normal incidence was analyzed (see Fig 4). The conductive tracks on both sides form the capacitive and inductive surfaces. As the FSS element was displaced on one side, opposite currents flow in the loop tracks increasing the mutual inductance and capacitance of the structure thereby shifting the stop band.

![Fig. 4. Transmission and Reflection response of double sided square loop FSS The Red line (-.-) and Green line (solid) represent the transmission and reflection response for the displacement of $\delta x = 0L_1$. The response is for normal plane wave incidence with $L_1 = 8$mm, $L_2 = 7.2$ mm, $p = 8$ mm, $w = 0.3$ mm, $t = 0.01$ mm, $h = 0.21$mm.](image)
Such displacements increase the bandwidth of the FSS. The simulated results show the maximum bandwidth was obtained by positioning the FSS such that the individual element sides of a bottom side lie at one half-cell apart in x and y direction to those of the top side when viewed from the normal angle of incidence. The results are given in Table 2.

Table 2: Transmission response of the double sided FSS with various configurations at normal wave incidence.

<table>
<thead>
<tr>
<th>Substrate thickness, h</th>
<th>Displacement</th>
<th>( f_r ) (GHz)</th>
<th>-10dB BW (GHz)</th>
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<td>0.2mm</td>
<td>( \Delta x )</td>
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<td>9.14</td>
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<tr>
<td>0.2mm</td>
<td>( \Delta y )</td>
<td>0</td>
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<td>0.5L _1</td>
<td>0</td>
<td>14.18</td>
</tr>
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<td>0.5L _1</td>
<td>0.5L _1</td>
<td>8.12</td>
</tr>
</tbody>
</table>

B. Angular sensitivity:

It is important that the FSS provides stable performance for various incident angles and different polarizations within its operating frequencies. In order to check the impact of incident angle, various incident angles (0°, 15°, 30°, 45°, 60°) were carried out for TE and TM polarizations. The results are given in Fig. 5.

![Fig. 5. Transmission coefficients as a function of frequency for various incident angles. (a) TE polarization (b) TM polarization.](image)

The double sided square loop FSS has a very small (less than 2%) change in resonant frequency for TE polarization compared to the TM polarization response. The general features of the stop band remains the same as that of the normal incidence for TE polarization. Fig. 5(a) shows a well-defined stop-band at 7.60GHz and the higher order resonances corresponding to higher angles appears unchanged. Fig. 5(b) shows the TM mode shifts by 6% (7.60GHz to 7.15GHz) within the 30° angle of incidence. For TM polarization, at higher angles (e.g. 45°, 60°) apart from the resonant frequency which is 7.13GHz and 6.90GHz respectively (Fig 6), the grating lobes also appear at 10.80 GHz and 11 GHz. This explains that for higher angle of incidence the FSS shows angular sensitivity.

![Fig. 6. The resonant frequency is a function of angle of incidence for TE and TM response. The grating lobes start to appear for angles greater than 30° for TM polarization.](image)

IV. BANDWIDTH

A. Substrate thickness:

The fundamental resonant frequency of the FSS is altered by changing the thickness of its supporting dielectric. With the increase in the thickness of the dielectric, the layer offset configurations show an initial decline of the resonant frequency from the free space value. The air/dielectric boundary is close to the conducting elements in this region. At the boundary, the low order evanescent Floquet modes decay exponentially with distance from the conducting elements. This modifies the relative amplitudes and the resonant frequency of the FSS with respect to the supporting dielectric layer [10].

For half period displacement in either \( x \) or \( y \) directions, the structure resonates at a higher frequency of about 14.18GHz with a bandwidth of nearly 9GHz for 0.21mm dielectric thickness. For the same thickness and half period displacement in the \( x \) and \( y \) directions, the structure resonates at a slightly lower frequency of 7.60GHz with a bandwidth of nearly 8.20GHz. This means that the half-cell displacement increases the mutual inductance, \( M_l \) and slightly the mutual capacitance, \( M_c \) (Fig. 1c) which lowers the band stop frequency. Beyond the thickness of 2mm, there is a periodic wave drop and rise in bandwidth. The peaks in the bandwidth curve are due to the combined effect of dielectric loading effect on two sides of the plastic and the back reflections from the plastic for a given substrate thickness. This effect causes broadening/narrowing of the curve near/at the quarter and half wavelength thicknesses of the plastic substrate [2].

B. Inter element spacing:

As the inter element spacing is increased, the mutual coupling decreases and this leads to grating lobes in the transmission curve which reduces the angular stability of the response. The mutual element coupling is unaffected by the change in the angle of incidence. Only the phase associated with the induced currents in the FSS elements change with angle of incidence [11].
The square lattice elements were placed following the general formula given in [12]. For normal incidence, $L_1/\lambda_0$ is less than 1. The plot in Fig. 7 shows that if the spacing is decreased to 0.2mm without changing the other parameters, the bandwidth is further enhanced by 2.3%. However, the printing tolerances need to be considered when designing any FSS structure. No grating lobes appear up to an inter element spacing of 2mm.

C. Track Width

Another geometrical parameter found to regulate the bandwidth of the FSS was the track width of the square loop(Fig. 8) where the circumference of the inner square loop changes, when all other parameters were unchanged. This is because the circumference for the flow of current is limited as the track width increases which lowers the inductance and shifts the frequency higher.

![Fig. 8](image)

Fig. 8. Simulated transmission response for the double sided square loop FSS with $x$ and $y$ offset bottom side, for different values of track width `$w$'. As the loop size decreases the inductance increases, narrowing the bandwidth seen for a track width of 0.1mm the bandwidth is 6.61GHz.

V. CONCLUSION

In this paper, we have presented a novel low profile double sided FSS screen printed on a single layer of thin flexible and transparent substrate with lateral displacements on one of the sides. The -10dB bandwidth (4.55GHz to 12.77GHz) was found for a unit cell periodicity of $\lambda_0/5$. The transmission coefficient for different incident angles shows that the FSS is independent of small incident angles. The bandwidth can be reduced or enhanced by optimizing the three parameters of the structure: substrate thickness, inter element spacing and track width. Apart from the promising future applications in radomes, curved surfaces and other antenna applications, the FSS can provide frequency shielding over ultra-wide bands in hospitals where there is potential risk of interference between various operating systems like medical equipment and mobile phones existing in close proximity. Also the simple printed FSS geometry on a transparent substrate retains the optical and RF transparency for required applications.

REFERENCES