Chapter 1

Introduction

Frequency selective surfaces (FSSs) are periodic structures designed on a substrate with metal (usually copper). These metallic structures behave like inductance and capacitance towards incident waves and hence behave as spatial filters. Therefore, an FSS either blocks or passes waves of certain frequencies in free space. Different shapes like a circle, square, cross, hexagon, tripole etc. can be used for FSS fabrication (on the metallic side of a dielectric substrate). Any of these specific shapes are placed periodically a half wavelength from one another (mostly in two dimensions). The wavelength is calculated from the frequency of operation (free space). An FSS can be designed to function as a high-pass, low-pass, bandstop or bandpass filter.

1.1 Motivation

With the advancement in telecommunication, the use of wireless technology for information system has drastically increased. It provides an advantage of getting rid of physical cabling but demands several issues to be addressed as well. The first issue is to provide security for information flow in wireless local area networks (WLANs).

Since WLANs are based on radio frequency (RF), the information can be tapped or hacked by intruders. The security issue gets even worse if the wireless data is classified. Unless the companies that develop WLAN systems, use expensive and powerful data encryption, it leaves confidential files and companies secrets to be vulnerable for hacking by an intruder. A bandstop FSS (operating at WLAN frequency) lined in the walls of buildings can provide a solution for wireless security. The frequency selective nature of FSS can allow third generation (3G), Global System for Mobile Communication (GSM), television and other emergency signals to pass through (while blocking WLAN).

The second issue is the interference of signals when different WLANs (with same frequency) operate in close proximity. The interference can also occur between WLAN and other devices such as bluetooth and microwave ovens. A bandstop FSS can be used in this case as well to isolate different signals from each other ultimately reducing the interference.

The third issue is to address the need of controlling the flow of energy waves between different mediums. A very common example is the front screen of a microwave oven, as used in houses and workplaces. One can notice a periodic structure of hexagons or circles on the front glass. This is in fact a high-pass FSS which stops microwaves from travelling through the front screen, since it is harmful to humans. However, it passes light waves.

The fourth issue is related to the electromagnetic architecture of buildings in which different useful frequency bands need to be provided in different parts of buildings on temporary basic. Therefore, an ON and OFF type FSS (called active FSS) can be used to address this issue as explained in Chapter 4 of this thesis.

Since FSSs are spatial filters, there are many challenges in their design:

- Since electromagnetic waves may strike the FSS from any arbitrary angle and may have different polarisations, the transmission and reflection properties of the FSS should have a stable frequency response when the angle of incidence or polarisation changes. Meeting these requirements involves careful design of the FSS parameters.

- An FSS can be both passive and active in its nature [1]. An FSS which has a static frequency response is called passive [2–4], while one with a variable frequency response is called active [5–7] . Most passive FSSs are periodic structures without any active device such as PIN or varactor diodes, while active FSSs may have active devices incorporated in the FSS structure. One particular disadvantage of the passive FSS is that, once designed there is no way to easily modify the reflection/transmission characteristics of array, without going through a redesign of geometry. The design of an active FSS is much more difficult and complex than the design of a passive FSS.

- An FSS, when used as an absorb/transmit filter, needs to be very compact in terms of the free-space wavelength. Also, for FSS absorbers based on the operation of the Salisbury screen [8–10], it is hard to achieve any transmission outside the stopband. Moreover, in most of these absorber designs [11–13], the distance between the FSS screen and the ground plane is $\lambda_0/4$. Hence absorbers for lower frequency bands may be impractical due to the greater distance between the two sheets of absorber.

This thesis presents both passive and active FSS designs for wireless communication applications. The FSS's response is stable for both perpendicular (Transverse Electric-TE) and parallel (Transverse Magnetic-TM) polarisations at normal and oblique angles of incidence (except the circular-loop active FSS presented in chapter 4). Three different types of FSS are presented: (a) Compact passive FSS absorb/transmit filter for 5.25 GHz WLAN applications, (b) Active FSS for 2.45 GHz WLAN applications, and (c) Passive bandpass FSS for energy-saving glass panels to improve transmission of useful RF/microwave signals.

1.2 Organisation of Thesis

An introduction to frequency selective surfaces is given in Chapter 2 to provide a basic insight to the readers about periodic structures and their applications in wireless technology.

Chapter 3 describes two novel dual-layer absorb/transmit frequency selective surfaces designed for 5 GHz WLAN applications. To the best of my knowledge, these are the first FSS designs that stop propagation of specific bands by absorbing as opposed to reflecting, while passing other useful signals. This is in contrast to conventional Salisbury and Jaumann absorbers, which provide good absorption in the desired band while the out-of-band frequencies are attenuated. Therefore, a special absorber was needed which can absorb signals in a particular stopband, while passing the other out-of-band useful signals. Two absorbers with such properties are successfully developed and presented in this chapter.

Chapter 4 describes an FSS that is electronically switchable between the reflective and transparent states. It can be used to provide a spatial filter to reconfigure the electromagnetic architecture of buildings. The FSS measurements show that the frequency response of the filter is sufficiently stable when the wave polarisation changes or the angle of incidence changes by up to 45°. However, theoretically, the active FSS has a sufficiently stable frequency response for both polarisations up to 60°. The FSS is based on a square-loop aperture geometry, with each unit cell having four PIN diodes placed across the aperture at 90° intervals. The PIN diodes have been placed orthogonally to each other to enhance the stability of the frequency response for both TE and TM polarisations. To minimise the effect of bias lines on the overall frequency response, a diagonal negative dc bias line, which is connected to the centre of the FSS unit cell, has been placed on the rear surface of the dielectric substrate. Positive dc biasing is provided from the front side of the printed structure. It is experimentally demonstrated that almost 10 dB of additional transmission loss can be introduced on average, at the resonance frequency for both polarisations, by switching the PIN diodes to the ON from the OFF state. Another active FSS configuration based on a circular-aperture geometry is also presented. It has a stable angle of incidence response for TE polarisation up to 45° while its TM response is not stable.

Chapter 5 describes characterisation work that was required as a prerequisite before designing frequency selective surfaces for modern-day glass to improve the transmission of wireless/mobile/cellular communication signals through the glass. The manufacturers of these glass panels apply very thin layers of metal-oxides on one side of the glass to provide extra infrared (IR) attenuation. These coatings block the infrared and ultraviolet waves to provide IR attenuation, but they also attenuate communication signals such as GSM 900, GSM 1800/1900, UMTS and 3G mobile signals. This creates a major communication problem when buildings are constructed with windows using this type of glass. A bandpass FSS can provide a solution to increase the transmission of useful bands through the coated glass. In order to design an appropriate FSS, the relative permittivity and conductivity of a glass should be measured accurately. Moreover, the electrical properties of the coated layer must also be known in order to obtain a resonance in the desired band. In this work, two different methods of measuring the permittivity and conductivity of glass were used. These characterisation requirements are addressed in this chapter. The electrical properties of one of the common glass panels (Optitherm™SN) are presented. On average, about 30 dB of attenuation is observed from 800 MHz to 6 GHz at normal incidence. To the best of my knowledge, the electrical values measured in this chapter were done for the first time and have not yet been considered in any other research.

Chapter 6 describes the design, prototyping and testing of a bandpass aperture-type cross-dipole frequency selective surface which is etched on the coated side of the energy-saving glass to improve transmission of RF/Microwave signals while preserving the thermal properties as much as possible. The FSS is required to have a sufficiently stable frequency response at normal and oblique incidence for both perpendicular (TE) and parallel (TM) polarisations, to be considered a good candidate for practical applications. Furthermore, the effect of etching an FSS on the transmission of RF/microwave, IR and visible light waves for two types of commercial energy-saving glass panels is also analysed. For example, an FSS with a 8 mm aperture designed to improve microwave transmission by 20 dB (from about -30 dB to -10 dB) at 1.3 GHz creates an increase in overall IR transmission from 23.8 % to 33.8 % (10%), which may be acceptable. An FSS with a narrower (4 mm) aperture improves microwave transmission by 16 dB with a 6.2 % increase in IR transmission. To the best of my knowledge, the research aspects discussed in this chapter are also considered for the first time and one of the publications on this topic won the best-paper prize in a conference as mentioned later in this chapter.

Chapter 7 provides the overall conclusion of the thesis. Commercial software packages used in the project are (a) High Frequency Simulation Software (HFSS) from ANSOFT (based on finite element method), and (b) CST Microwave Studio (uses finite integration technique).

1.3 Original Contributions

The main contributions of this thesis are outlined as follows:

- The absorb/transmit FSSs presented in Chapter 3 are the first spatial filters that stop propagation of specific bands by absorbing as opposed to reflecting, while passing other useful signals. Traditional FSS absorbers can only absorb a particular frequency band of interest, while transmission outside the band is attenuated. Salisbury and Jaumann absorbers are the typical examples.

- Chapter 4 presents a single-layer switchable bandpass FSS which has a stable frequency response for oblique TE and TM incidences. The single-layer configuration circumvents the problems of more complicated multi-layer switchable FSS designs presented in the literature. Also, the dc biasing technique used in the design has a minimal effect on the overall electromagnetic behaviour of the active FSS.

- Chapter 5 and 6 present the FSS solution to enhance useful RF/microwave signals through energy-saving glass. The effect of etching an FSS on the transmission of RF/microwave, Infrared (IR) and light (visible) waves for two types of commercial energy-saving glass panels is analysed. The authors of previous research did not consider this multi-disciplinary aspect of FSS design. Moreover, the dielectric constant and conductivity of the glass are practically measured using waveguide and parallel plate capacitor techniques to obtain more accurate results (in contrast to previous related research).

1.4 Research Collaborations

Research collaborations with different institutions and organisations were carried out during the course of the PhD work. The names of the institutions and organisations are listed below. The work carried out and their contribution are given in detail.

University of Sheffield, UK

On an invitation from Professor Richard Langley, Head of Communication Group, Department of Electronic and Electrical Engineering, I visited the Department in July 2006 for 8 weeks. Dr Lee Ford from the same group was appointed as my supervisor and we worked on circular and square-loop active FSSs as presented in Chapter 4. The reflection measurement facility at the Department was used for measurements of the dual-layer stable FSS absorber and both active FSSs. Dr Ford performed the reflection measurements. He is a co-author in the related publications.

Loughborough University, UK

Professor Yiannis Vardaxoglou, Head of Department of Electronic and Electrical Engineering, allowed me to use their transmission measurement facility in August 2006. Dr Chinthana Panagamuwa helped in the transmission measurement of the absorb/transmit FSS absorber and both circular and square loop active FSSs. This collaboration has been acknowledged in the publications.

Kent University, UK

Dr John Batchelor and Professor Ted Parker from the School of Engineering and Digital Arts allowed me to visit their transmission measurement facility. The circular aperture active FSS presented in this thesis was measured for transmission at this facility. This work has been acknowledged in the publications as well.

Lund University, Sweden

Professor Anders Karlsson, from the Department of Electrical and Information Technology, invited me for research collaboration on employment of frequency selective surfaces in energy-saving glass. This work has been presented in Chapters 5 and 6. Professor Karlsson helped with the impedance boundary condition for glass coating and guided in the measurement of electrical properties of the glass. Professor Lars Olsson from the same Department also helped with waveguide setup construction and the transmission measurement of energy-saving glass. He also advised on how to select an FSS element type to employ in glass for an FSS solution. Mr Martin Nelsson helped in etching the FSS on the coated side of the glass. Due to the fragile nature of the glass, the milling machine damaged a lot of tools. However, Mr Martin used his experience to complete the job without further damage to milling tools. All of these people have been acknowledged as co-authors in related publications.

Pilkington, Halmstad, Sweden

Without the help from industry, it would have been difficult to devise a practical solution for energy-saving glass. Mr Alf Rolandsson and Mr Roland Borjesson from Pilkington supported the research and provided different types of commercial glass panels for the project. Both small and large sizes were provided. A visit to the factory was also arranged to help us understand the manufacturing process. They also provided the values of surface resistivity for different types of glass coatings having commercial confidentiality. Also, Ms Cartrina Karlsson from the same organisation conducted the infrared and visible wavelength measurements presented in chapter 6. The efforts and support of these people has been acknowledged in the publications.

1.5 List of Publications

The following publications are the direct outcome of my PhD thesis. I was the main contributor to all these publications.

Journal Papers

1. **Ghaffer I. Kiani**, Kenneth L. Ford, Lars Olsson, Martin Nilsson, Chinthana Panagamuwa, and Karu P. Esselle, "*Switchable Frequency Selective Surface for Reconfigurable Electromagnetic Architecture of Buildings*", IEEE Transactions on Antennas and Propagation (Accepted for publication, October 2009).

2. **Ghaffer I. Kiani**, Kenneth L. Ford, Karu P. Esselle, Andrew Weily, and Chinthana Panagamuwa, "*Angle and Polarization Independent Bandstop Frequency Selective Surface for Indoor Wireless Systems*", Microwave and Optical Technology Letters, Volume 50, Issue 9, September 2008, Pages: 2315-2317.

3. **Ghaffer I. Kiani**, Kenneth L. Ford, Karu P. Esselle, Andrew Weily, Chinthana Panagamuwa, and John Batchelor, "*Single-Layer Bandpass Active Frequency Selective Surface*", Microwave and Optical Technology Letters, Volume 50, Issue 8, August 2008, Pages: 2149-2151.

4. **Ghaffer I. Kiani**, Kenneth L. Ford, Karu P. Esselle, Andrew Weily, and Chinthana Panagamuwa, "*Oblique Incidence Performance of a Novel Frequency Selective Surface Absorber*", IEEE Transactions on Antennas and Propagation, Volume 55, Issue 10, October 2007, Page(s): 2931-2934.

5. **Ghaffer I. Kiani**, Andrew Weily, and Karu P. Esselle "*A Novel absorb/transmit FSS for Secure Indoor Wireless Networks with reduced Multipath Fading*", IEEE Microwave and Wireless Components Letters,Volume 16, Issue 6, June 2006, Page(s): 378-380.

6. **Ghaffer I. Kiani**, Anders Karlsson, Lars Olsson, and Karu P. Esselle, "*Transmission of Infrared and Visible Wavelengths Through Energy Saving Glass due to etching of Frequency Selective Surfaces*", IET Proceedings on Microwaves, Antennas and Propagation (Revised manuscript under review, 2009).

7. **Ghaffer I. Kiani**, Anders Karlsson, Lars Olsson, Martin Nilsson, and Karu P. Esselle, "*Cross-Dipole Bandpass Frequency Selective Surface for Energy Saving Glass Used in Buildings*", IEEE Transactions on Antennas and Propagation (Revised manuscript under review, 2009).

Conference Papers

1. **Ghaffer I. Kiani**, Anders Karlsson, Lars Olsson, and Karu P. Esselle, "*Transmission Analysis of Energy Saving Glass Windows for the Purpose of Providing FSS Solutions at Microwave Frequencies*", IEEE Antennas and Propagation Society International Symposium, San Diego, California, USA, 5-11 July 2008, Page(s): 1-4.

2. **Ghaffer I. Kiani**, Anders Karlsson, Lars Olsson, Karu P. Esselle, and Martin Nilsson, "*Transmission Improvement of Useful Signals through Energy Saving Glass windows using Frequency Selective Surfaces*", Workshop on Applications of Radio Science (WARS) Conference, Gold Coast, Queensland, Australia, 10-12 February, 2008 **(Won Best Paper Prize)**.

3. **Ghaffer I. Kiani**, Karu P. Esselle, Andrew Weily, and Kenneth L. Ford, "*Active Frequency Selective Surface using PIN diodes*", IEEE Antennas and Propagation International Symposium, Honolulu, Hawaii, USA, 9-15 June 2007, Page(s): 4525-4528.

4. **Ghaffer I. Kiani**, Anders Karlsson, Lars Olsson, and Karu P. Esselle, "*Glass Characterization for Designing Frequency Selective Surfaces to improve transmission through energy saving glass windows*", Asia Pacific Microwave Conference (APMC), Bangkok, December, 2007.

5. **Ghaffer I. Kiani**, Kenneth L. Ford, Karu P. Esselle, and Andrew Weily, "*Oblique Incidence Performance of an Active Square Loop Frequency Selective Surface*", 2nd European Conference on Antennas and Propagation (EuCAP), Edinburgh, UK, 11-16 November, 2007.

6. **Ghaffer I. Kiani**, Karu P. Esselle, Andrew Weily, and Kenneth L. Ford, "*Active Frequency Selective Surface design for WLAN*", 10th Australian Symposium on Antennas, Sydney, Australia, 14-15 February, 2007.

7. **Ghaffer I. Kiani**, Andrew Weily, and Karu P. Esselle, "*Frequency Selective Surface Absorber using Resistive Cross-Dipoles*", IEEE Antennas and Propagation Society International Symposium, Albuquerque, New Mexico, USA, 9-14 July 2006, Page(s): 4199-4202.

Chapter 2

Frequency Selective Surfaces

2.1 Background

An American Physicist David Rittenhouse discovered in 18th century that, some colours of a light spectrum are suppressed when a street lamp is observed through a silk handkerchief [14]. This frequency selective property of handkerchief proved the fact that, surfaces can exhibit different transmission properties for different frequencies of incident wave. Hence, such surfaces are now called frequency selective surfaces (FSSs). Therefore an FSS can be considered as a free-space filter which could be used to pass certain frequencies and stop others. These spatial filters are designed by fabricating periodic geometric metallic patterns on a dielectric as shown in Fig. 2.1.

To understand the concept of spatial filtering, consider an incident wave striking a metal surface as shown in Fig. 2.2 [15]. Imagine a single electron in the surface plane with a direction vector perpendicular to the plane. The E-vector of the incident wave is parallel to the metallic surface. Therefore, when the incident wave strikes the metal surface, it exerts a force on the electron causing it to accelerate in the direction of E-vector. In order to keep the electron in a continuous oscillating state, some

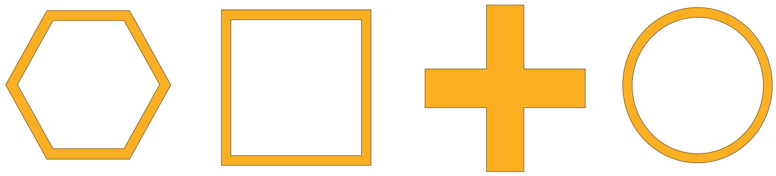

Figure 2.1 Different element shapes which are popular in FSS design.

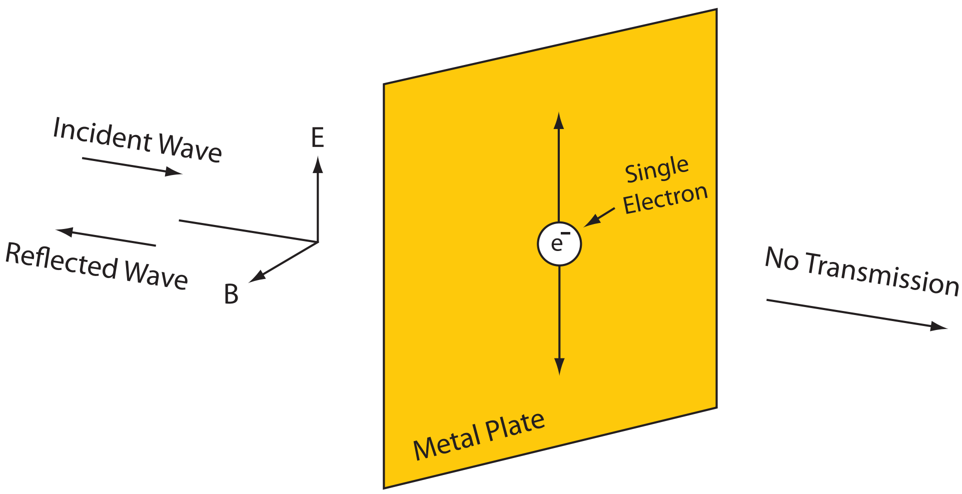

Figure 2.2 Electron in the plane oscillates due to the force exerted by incident wave resulting in low transmittance.

portion of energy must therefore be converted into the kinetic energy of the electron. This will result in absorption of most of the incident energy by the electron and is reflected (Low Transmittance). The transmission through the filter will be zero if all the energy of incident wave is converted to the kinetic energy for the electron.

Referring to Fig. 2.3, in which the direction vector of the electron is perpendicular to the E-vector of incident wave. In this case, despite of force exerted by the E-vector, the electron is constrained to move along the direction vector. Hence the electron is unable to absorb the kinetic energy of incident wave. Therefore, the wave is not absorbed and a high transmittance occurs.

FSSs may be singly, doubly or triply periodic to perform a filter operation. Stacking multiple FSSs together, usually with each separated by a dielectric layer, is also

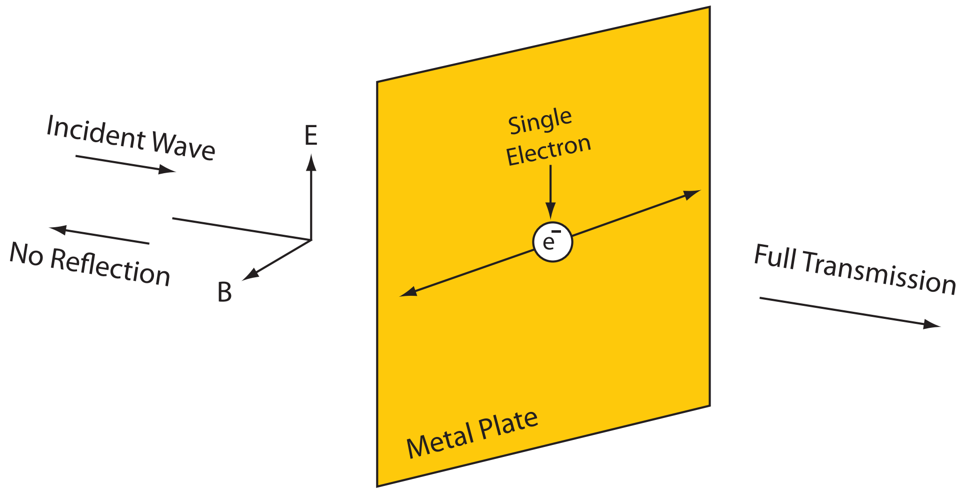

Figure 2.3 Electron is constrained to move and hence unable to absorb energy resulting in high transmittance.

common [16–27]. FSSs are divided into four filter types, depending on their physical construction, material and geometry, as described in Section 2.2. Fig. 2.4 shows a triply periodic FSS using cross dipoles, which can be considered as a 3D photonic crystal.

Since the beginning of the 20th century, FSS has been an important topic of research. Marconi and Franklin patented their work on FSS reflector for use in wireless telegraphy and telephony in 1919 [28]. However in the 1960s [29, 30] FSSs study became very popular.

2.2 FSS Filter Types

As mentioned before, FSSs are filters that can be designed to give four standard filter responses: bandstop, bandpass, high-pass and low-pass. Babinet's principle can be employed to transform from bandstop FSS to bandpass FSS, from low-pass FSS to high-pass FSS, and vice versa, provided that the structure is symmetrical. This means that, to transform a high-pass filter into a low-pass filter, the conductive

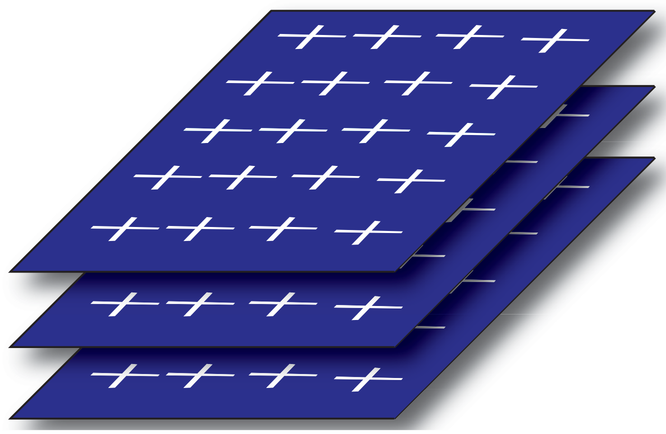

Figure 2.4 A cascaded FSS.

and non-conductive elements are reversed as shown in Fig. 2.5. An appropriate FSS element is chosen depending upon the design criteria, such as the level of attenuation, bandstop/bandpass frequency, bandwidth, and sensitivity to electromagnetic wave incidence angle. Typical examples of the four filter types are as follows.

2.2.1 Low-Pass FSS

These are typically of the mesh type as presented in Fig. 2.5 a. They can be constructed by perforating a conductive sheet (leaving behind an array of patches).

2.2.2 High-Pass FSS

High-Pass FSS can be the Babinet complement of the low-pass FSS as shown in Fig. 2.5 b. It is the complement of the FSS in Fig. 2.5 a.

2.2.3 Bandstop FSS

It appears in the form of periodic arrays of conductive elements of the following geometries: circular, square or hexagonal loops, cross dipoles, tripoles etc. This FSS

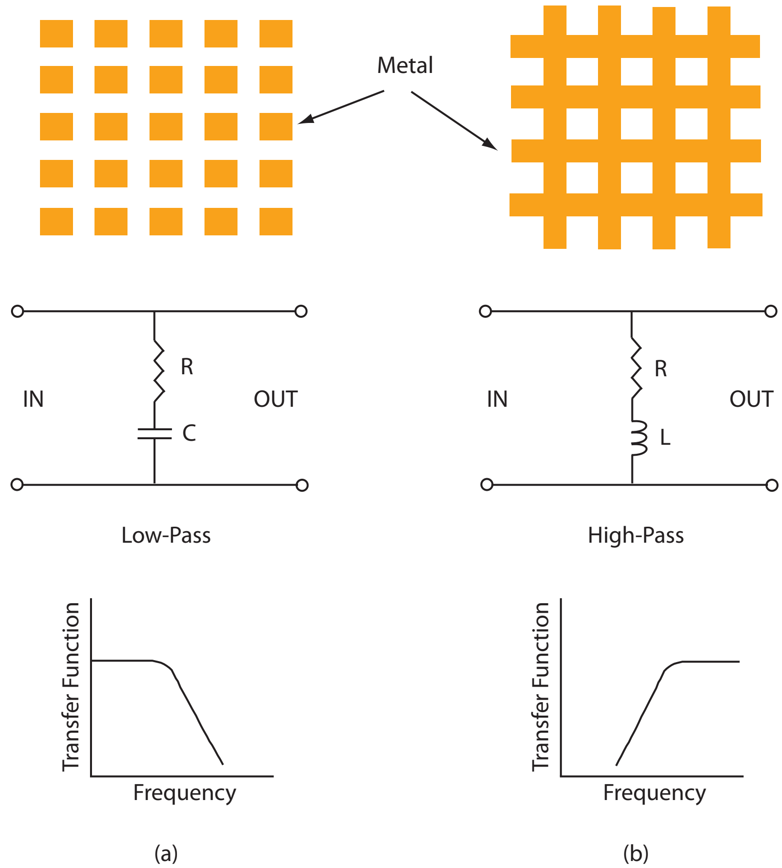

Figure 2.5 (a) Low-pass and (b) High-pass FSSs with their corresponding equivalent circuits and frequency response.

has probably been the most widely used. A typical cross dipole structure is shown in Fig. 2.6 a.

2.2.4 Bandpass FSS

A typical bandpass FSS is shown in Fig. 2.6 b. It is the Babinet complement of the bandstop filter in Fig. 2.6 a.

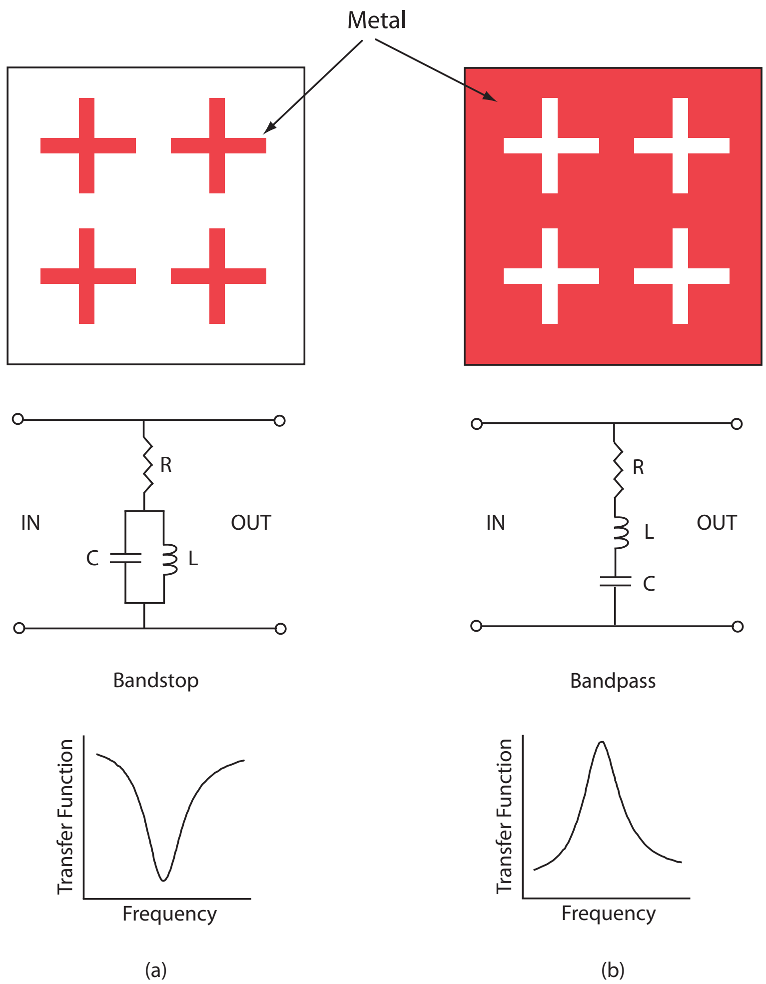

Figure 2.6 (a) Bandstop and (b) Bandpass FSSs with their corresponding equivalent circuits and frequency response.

2.3 FSS Equivalent Circuits

The FSS filter response of a particular geometric shape can be related to its equivalent circuit. Capacitive and inductive FSSs derive their names from circuit theory. Fig. 2.5 shows a low-pass and a high-pass FSSs with their corresponding equivalent circuits, while Fig. 2.6 shows the equivalent circuits for bandstop and bandpass FSSs. In short, we can say that an FSS behaves like a series or parallel RLC circuit (or a combination of both) depending on the design of the low-pass, high-pass, bandpass or bandstop characteristics.

2.4 FSS Elements Groups

The four basic FSS filters described in Section 2.2 may be combined [1] to generate many other novel FSSs with unique characteristics. Multiband nature, angular stability, polarisation independence, bandwidth and reduced FSS sizes are few characteristics that can be obtained by combination of FSS elements. As shown in Fig. 2.7, FSS elements can be categorised into four basic groups [1], these being

- Group 1: N-poles or Centre Connected such as dipoles, tripoles, square spirals and Jerusalem crosses.
- Group 2: Looped types, such as circular, square and hexagonal loops.
- Group 3: Solid interior or patch types of various shapes.
- Group 4: Combinations of any of the above.

These FSS element and their combinations have been used by researchers for different applications and have published their work as well. A summary of each group is described here:

2.4.1 Group 1: Centre Connected

Cross dipoles [3, 31, 32], tripoles [33–35]; and the Jerusalem Crosses [4, 36–38] are the most popular members of this group. These elements have also been combined with other element types to produce different novel FSSs [1, 39].

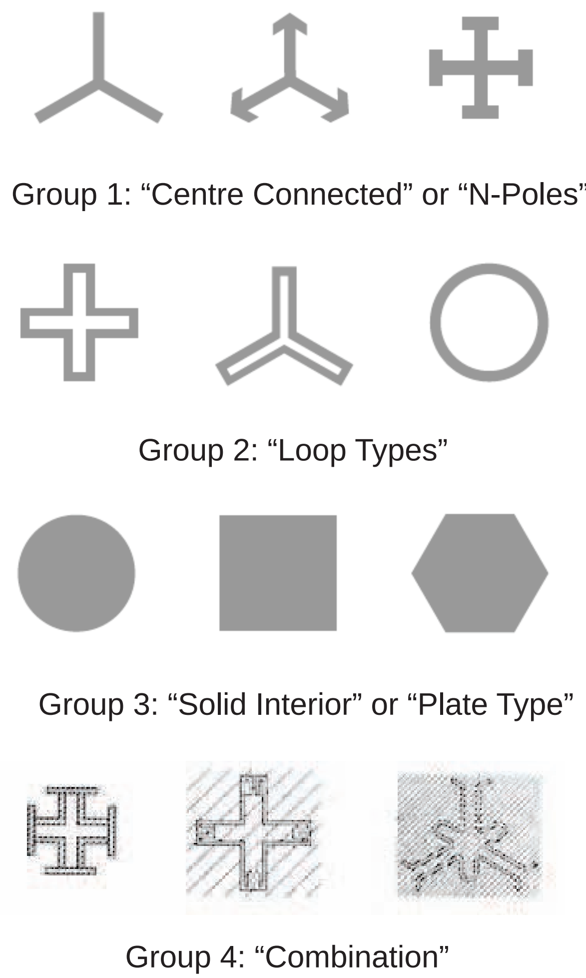

Figure 2.7 Typical element types arranged in groups.

2.4.2 Group 2: Loop Types

This group is probably the most popular. Square loops [40–45], rings [2, 40, 46–51] and looped tripoles [1, 33, 52] are members of this group.

2.4.3 Group 3: Solid Interior Types

Patch type FSS belong to this group [53–58]. Both single or multi-layer configurations are possible [59].

2.4.4 Group 4: Combinations

The combinations of FSS element [1, 60, 61] can be helpful in resolving the issue of angular stability with different polarisatons which may be difficult to achieve with single-element FSSs [13, 62, 63].

2.5 Passive and Active FSS

An FSS may be classified into two different types based on the ability to dynamically reconfigure spatial filtering characteristics. The two main types are:

- Passive FSS
- Active FSS

A passive FSS is one in which periodic structures are fabricated on a dielectric sheet for a particular frequency to be transmitted or reflected. Once this surface is fabricated, its properties cannot be altered. The important point here is that they have to be large enough to be pasted on a large cross-section of a wall or a window to either block or pass the desired signal. The advantage of these FSSs is that they are easy to design and manufacture, but the disadvantage is that they are not reconfigurable. Fig. 2.8 illustrates a finite 3×3 passive cross-dipole FSS.

On the other hand, an active FSS is made up of periodic structures that incorporate active devices like PIN diodes or varactor diodes in the FSS model (Fig. 2.9). By tuning these active devices by an external stimulus (dc power supply), the FSS becomes reconfigurable. The disadvantages of such surfaces include the cost of manufacturing, power consumption and the need for a dc power source.

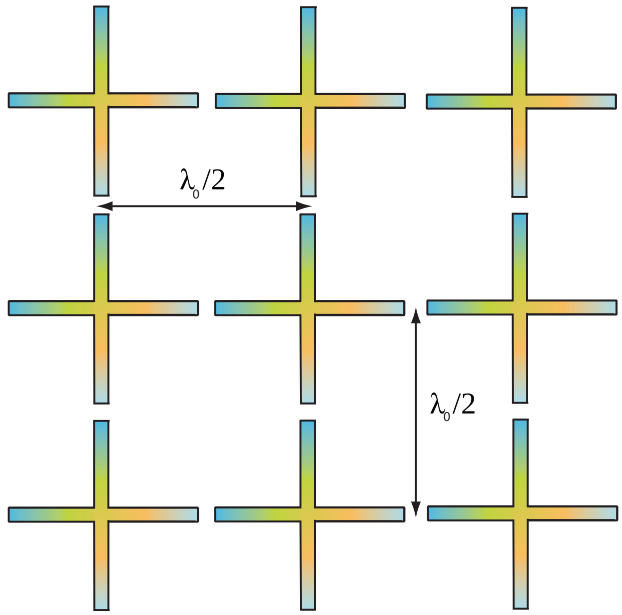

Figure 2.8 A finite 3×3 passive cross-dipole FSS.

2.6 Analysing an FSS

The theoretical foundation for FSSs is provided by the phased array antenna theory [30, 64]. There are different techniques to analyse FSS filters which are presented in this section.

2.6.1 Circuit-Theory Technique

This technique utilises a quasi-static approximation to derive the equivalent circuit model for the FSS [29, 65, 66]. It provides quite accurate results for simple FSS designs at normal incidence only. However, modelling an equivalent circuit of an FSS for oblique incidence is difficult and may not provide very accurate results [67] (as compared to full wave simulations).

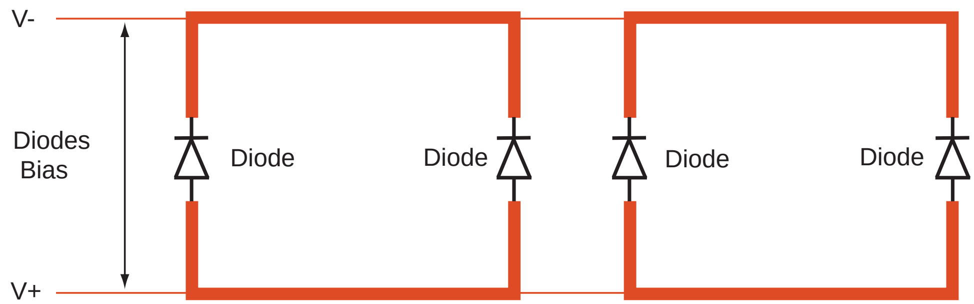

Figure 2.9 An active square loop FSS with PIN diodes.

2.6.2 Modal Expansion Technique

Modal expansion technique uses Floquet modes in space which are matched with the aperture modes to form an integral equation. This integral equation is then solved by using method of moments [1,68–74] or the conjugate gradient technique [14,75]. Most FSS analysis has been done using modal expansion techniques with a high degree of accuracy [76].

2.6.3 Iterative Technique

This technique [76–78] avoids large matrix storage requirements, by using iteration. The current on the surface of the conducting region is iterated. Different techniques have been discussed on the basis of merit by Wu [76]. This method also provides high accuracy in predicting spectral response of FSSs.

In this thesis, finite element method (Ansoft HFSS) [79–81] and finite integration technique (CST Microwave Studio) [82–84] are used for analysing FSS structures.

2.7 Applications of FSSs

A FSS could be used in many engineering applications such as:

- Radio Frequency Identification (RFID) Tags
- Collision avoidance
- Radar Cross-Section Augmentation
- Robotic guided paths
- Electromagnetic interference (EMI) Protection
- Photonic band-gap structures
- Dichroic subreflectors in parabolic reflector antennas
- Low probability of intercept systems (e.g stealth) including radomes
- Waveguide or cavity control coupling
- Wireless Local Area Network (WLAN) security

As an example, the application of FSS as a dichroic subreflector for parabolic reflector antennas is shown in Fig. 2.10. The FSS is totally reflecting at feed 1 and totally transparent for feed 2. Therefore, two independent feeds may share the same reflector antenna simultaneously.

One other application of FSSs is their use in wireless security. For example, the mobile phone signals could be used to set off an explosion. Also, a mobile phone ringing in the cinema, theatre or in places of religious worship is very annoying. FSSs could be used to block mobile signals for the above mentioned problems. Wideband noise sources can also be used to jam these signals, but they require continuous power source and may malfunction at times.

The same applies to wireless local area networks (WLANs) where data could be breached by an outsider if proper security measures are not taken. Previously, the

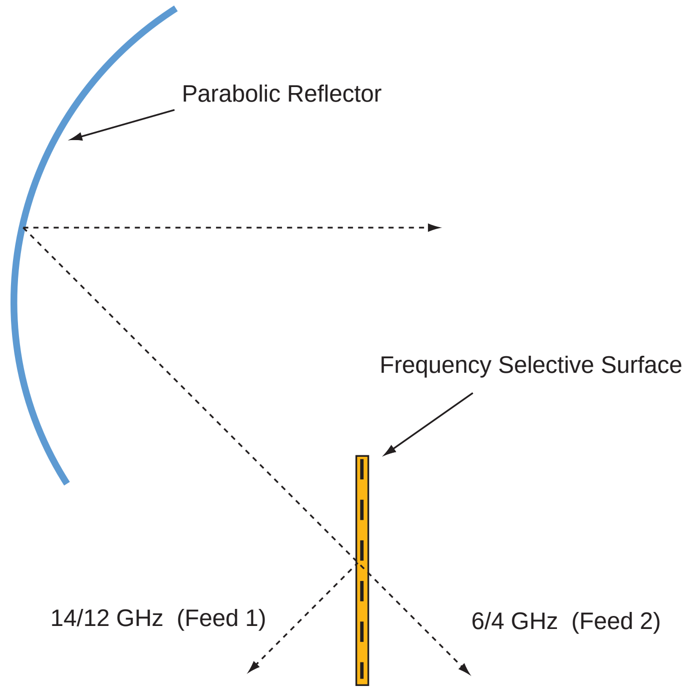

Figure 2.10 Reflector antenna system using frequency selective surface for dual-feed.

solution to this problem was to turn offices and buildings into a signal-proof "Faraday cage", by lining the walls with aluminum foil, and using glass that absorbs radio waves in the windows. This helped in absorbing all the electromagnetic waves from different wireless sources. However, the problem with such configuration was that, no one could use mobile phone etc. inside the offices or buildings. Therefore, certain types of FSS can be designed in order to prevent WLANs signals escaping from a building without blocking mobile phone and other useful signals. These aspects are discussed in Chapters 3 and 4 of this thesis due to the importance of the topic.

2.8 Conventional Absorbers

2.8.1 Salisbury Screen

This type of absorber was named after its inventor, W.W. Salisbury of the MIT Radiation Laboratory, who was issued a patent in 1952 [1]. Its first design was applied in ship radar cross section (RCS) reduction. There have been many design refinements over the years [8–10] especially because of the increasing interest for stealth planes, but the principles remain the same.

Salisbury screen design consists of a ground plane which is the metallic surface that needs to be concealed, a lossless dielectric of a given thickness (a quarter of the wavelength at the design frequency) and a thin lossy screen. Fig. 2.11 shows the configuration of a typical Salisbury screen with its equivalent circuit and frequency response [85].

The principle of working is as follows:

- The incident wave is split into two (equal in intensity) waves that have the same wavelength (λ).
- The first wave is reflected by the exterior surface (the thin lossy screen) while the second beam travels through the dielectric, and it is reflected by the ground plane (which is the most inner layer of the Salisbury screen).
- The two reflected waves interfere and cancel each other's electric fields [86].

There are a few disadvantages inherent to this model (some of which have been solved [8, 9]). Salisbury screens are very narrow band and become impractical at low frequency applications due to its $\lambda_0/4$ distance between the ground plane and the resistive sheet. Oblique incidence stability also remains a challenge.

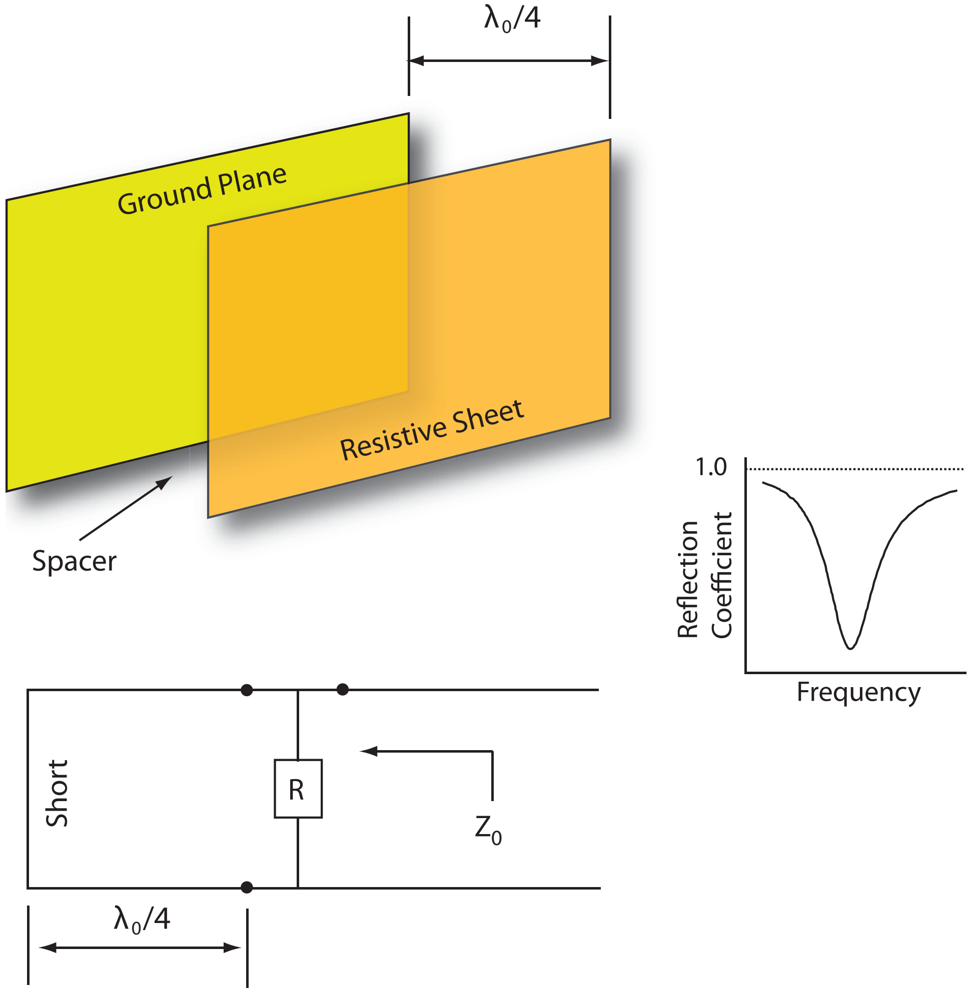

Figure 2.11 Conventional Salisbury screen with its equivalent circuit and frequency response.

2.8.2 Jaumann Absorber

A Jaumann absorber or Jaumann layer is a radar absorbent device [1,13,87,88]. When first introduced in 1943, the Jaumann layer consisted of two equally-spaced reflective surfaces and a conductive ground plane. One can think of it as a generalized, multi-layered Salisbury screen as the principles are similar.

Being a resonant absorber (i.e. it uses wave interfering to cancel the reflected wave), the Jaumann layer is dependent upon the $\lambda_0/4$ spacing between the first reflective surface and the ground plane and between the two reflective surfaces (with a total thickness of $\lambda_0/4 + \lambda_0/4$). Fig. 2.12 shows the configuration of a typical Jaumann absorber with its equivalent circuit and frequency response.

Because the wave can resonate at two frequencies, the Jaumann layer produces two absorption maxima across a band of wavelengths (if using the two layers configuration). These absorbers must have all of the layers parallel to each other and the ground plane that they conceal.

More elaborate Jaumann absorbers use series of dielectric surfaces that separate conductive sheets. The conductivity of these sheets increases with proximity to the ground plane. However, these absorbers have disadvantage of having larger distance between the sheets. Also, to achieve an oblique incidence stability, the distance between the sheets needs to be increased further, hence making the design impractical for lower frequencies [87].

2.9 Energy-Saving Glass

Energy-saving glass is very common is modern architecture of buildings. A thin metal-oxide coating is deposited on one side of the ordinary glass to provide thermal isolation while keeping good see-through effects. However, it also blocks the transmission of useful signals as described in Section 2.11. Fig. 2.13 describes the way an energy-saving glass window reacts to different frequencies [89, 90]. It provides good thermal isolation as well as WLAN security, but poor transmission for mobile phones and other useful frequencies remains a major drawback.

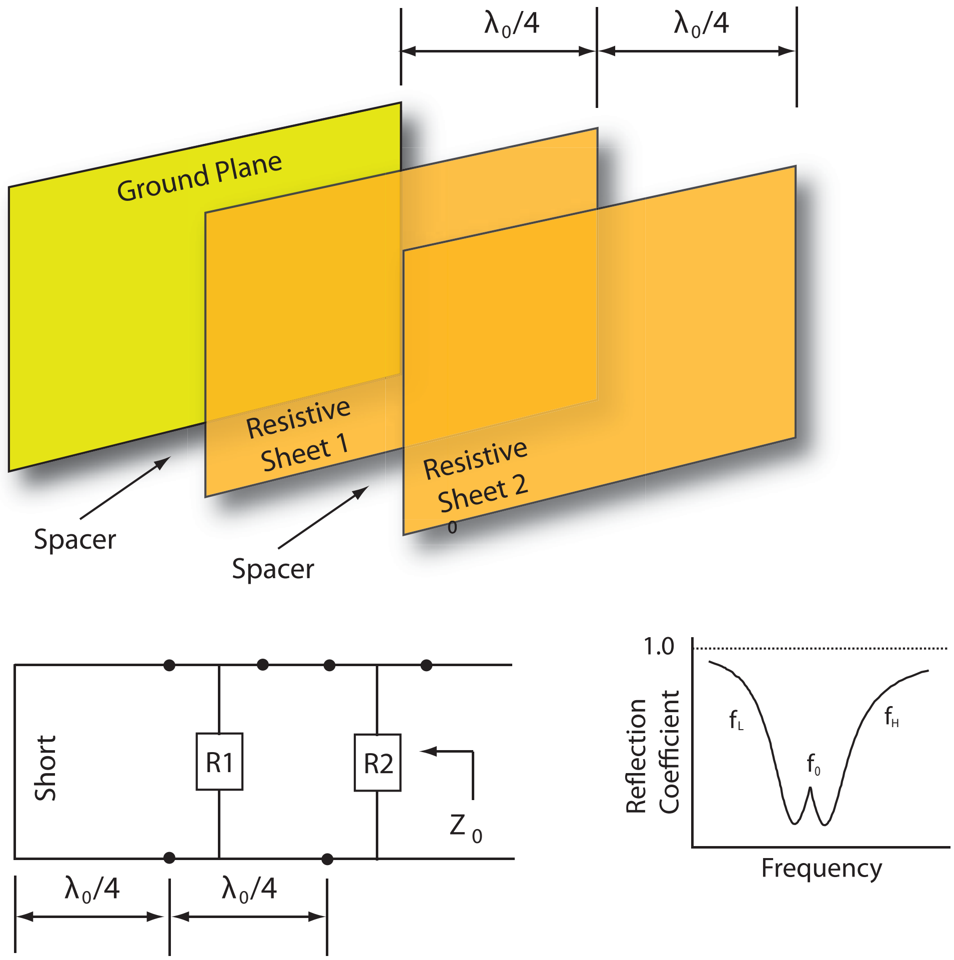

Figure 2.12 Conventional Jaumann absorber with its equivalent circuit and frequency response.

2.10 Definition of Polarisation for Oblique Angle Incidence

This thesis describes oblique incidence performance of various FSS designs for both TE and TM polarisations. Therefore, definitions of polarisations for oblique incidence are given in this section.

Polarisation is defined as the orientation of electric field in a propagating electromagnetic wave. When the electric field is perpendicular to the plane of incidence, the

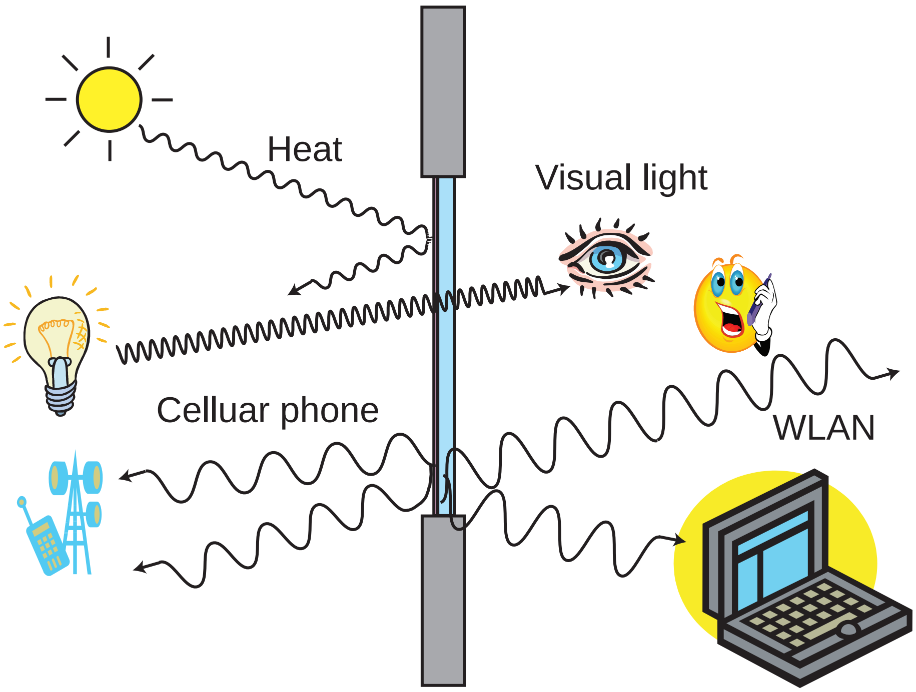

Figure 2.13 Energy-saving glass window showing transmission properties of different frequencies (small percentages of wave absorption in all the cases are not shown).

polarisation is called perpendicular (Transverse Electric-TE) polarisation, and when it is parallel to the plane of incidence, then it is called parallel (Transverse Magnetic-TM) polarisation [91]. The plane of incidence is defined as the plane formed by a unit vector normal to the reflecting interface and the vector in the direction of incidence. To analyse reflection and transmission at oblique angles of incidence for a general wave polarisation, it is convenient to decompose the electric field into its parallel and perpendicular components (relative to the plane of incidence) and analyse each of them individually. The total reflected and transmitted field will be the vector sum from each one of these polarisations. Figs. 2.14 and 2.15 show a plane wave incident obliquely on a plane dielectric boundary for perpendicular and parallel polarisations.

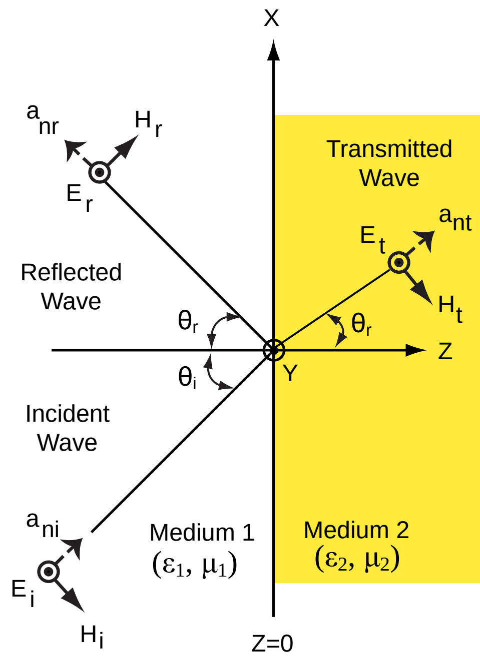

Figure 2.14 Plane wave incident obliquely on a plane dielectric boundary (Perpendicular Polarisation).

2.11 Justification of this Research

During the literature review, three main areas in FSS technology were identified as good candidates for future research.

1. FSSs have been considered for applications such as wireless security, radomes, antennas and telecommunications [92]. Common FSSs, which are of the reflect/transmit type, can be incorporated in the walls of buildings to provide wireless local-area network (WLAN) security. They block WLAN signals, while passing cellular phone signals [93] but give rise to heavy stopband reflections from the FSS surface, causing additional delay spread and multi-path fading in WLAN systems. Research has recently been undertaken to use lossy FSSs as absorbers [7, 94, 95] in other applications. The main challenges in these designs are (a) to achieve stable response for oblique incidence for both polarisations

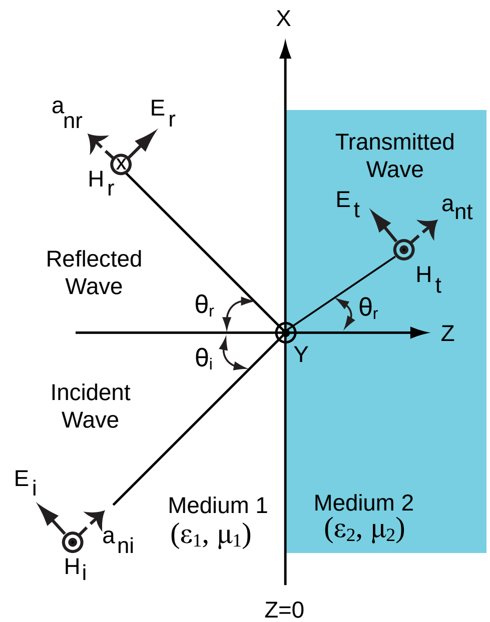

Figure 2.15 Plane wave incident obliquely on a plane dielectric boundary (Parallel Polarisation).

(TE and TM) and (b) to reduce the distance between the FSS and the resistive sheets to achieve a compact design [11, 12] without compromising absorption performance. Moreover, research has also been carried out to achieve a stable frequency response for oblique angles from circuit-analogue absorbers at both parallel and perpendicular polarisations [13]. However, in all these absorber designs, there is no sufficient transmission of useful signals outside the band of interest. One of the the FSS absorber designs which is presented in Chapter 3 is approximately 2 times more compact than standard $\lambda_0/4$ designs and passes the out-of-band useful frequency signals as well (as opposed to the designs presented in the previous research).

2. Recently, a considerable amount of research has been carried out in the field of switchable FSSs to achieve a reconfigurable frequency response for different applications [5, 6, 96–99]. Among different methods to obtain a variable FSS

frequency response, PIN diodes are commonly used to switch an FSS between the ON and OFF states. Most research has been carried out on bandstop FSSs, such as arrays of metallic dipoles, which have a switching device (e.g. diode) placed across the dipoles that can be varied via some external stimulus. Conversely, the bandpass version consisting of an array of slots is not suitable for the inclusion of active elements, as the bias applied to the devices will short across the metal surface. Recently, an attempt was made to design an active bandpass FSS using two FSS layers [100]. In this design, one of the FSS layers is a standard bandstop active FSS, which is placed in front of a passive bandpass FSS with a thin layer of PCB. This design has the disadvantages of requiring dual-layers, accurate design tools and high manufacturing accuracy. Also, the dc biasing used in many of the previously designed active FSSs is very complex. In order to alleviate these constraints, a single-layer switchable FSS is presented in Chapter 4. It has a stable frequency response for oblique TE and TM incidences and has a relatively simple biasing technique. An average additional measured transmission loss of 10 dB is achieved for both polarisations at normal and oblique incidence, by switching PIN diodes between reverse and forward bias. This means that a ten times loss occurs in tranmission power between ON and OFF states of FSS which may be acceptable for a single layer active FSS configuration. However, higher power loss may be obtained using dual layer complex active FSS structures [100]. This active FSS can easily be used to electronically reconfigure the electromagnetic architecture of buildings.

3. Energy-saving glass is very popular in the design of modern buildings due to its low-emissivity properties [89, 90, 92, 101]. This energy-saving property is achieved by applying a thin coating of metallic oxide on one side of ordinary float glass. This coating provides good thermal isolation to the buildings by

blocking infrared rays while being virtually transparent to the visible part of the spectrum. Therefore, visibility through the glass remains good while the buildings can be kept cool for a longer period of time in summer. The reverse is true for winter. However, there is one drawback associated with these energy-saving glass panels. Due to the presence of the metal-oxide coating, these glass panels also attenuate many useful RF/microwave signals [89, 90, 101]. Most of these signals fall within the frequency band of 800 MHz to 2200 MHz. Signals of GSM mobile phones, personal communication, GPS and 3G systems are examples. In order to improve the transmission of these useful signals through the coated glass, an aperture-type frequency selective surface can be used [1]. Such an FSS can provide a good transmission improvement in the desired band while maintaining the IR attenuation at an acceptable level.

Research has been carried out recently to provide an FSS solution for this problem [89, 90, 101]. In this research, the authors have presented interesting results and ideas for FSS design and measurement, but some important parts of this research were based on assumptions, or no direct comparison between theoretical and measured results was presented. For example, the relative permittivity of glass was chosen arbitrarily from 3-7 [89] while none of the measured values of glass conductivity or coating properties was used in the simulations. Therefore, accurate measurements of the relative permittivity and conductivity of the glass and the electrical properties of the coating surface were essential for a reliable design of bandpass FSS for energy-saving glass. These properties have been measured in chapter 5 for the first time to be able to provide a more practical solution. Furthermore, the effect of etching an FSS on the transmission of RF/microwave, Infrared (IR) and light (visible) waves for two types of commercial energy-saving glass panels is also analysed in Chapter 6. This important design aspect was not considered before in any related research.

Chapter 3

Absorb/Transmit Frequency Selective Surface Absorber

To address the issues described in section 2.10, two novel dual-layer absorb/transmit FSS designs are presented in this chapter for 5 GHz WLAN applications. Please note that 2.45 GHz WLAN band is not selected for FSS designs presented in this chapter because (a) The 5 GHz bands have much greater spectrum available. In this band there are 12 non-overlapping channels, each with 20 MHz of bandwidth. This means significantly better performance as compared to the 2.45 GHz band. The entire 2.45 GHz band is 80 MHz wide, which only allows three non-overlapping channels (b) 2.45 GHz WLANs can experience interference from cordless phones, microwaves, and other WLANs. The interfering signals degrade the performance of 2.45 GHz WLAN by periodically blocking users and access points from accessing the shared air medium and (c) 5 GHz systems can provide enhanced security over 2.45 GHz systems because of its less transmission range [102].

The first FSS absorber has good absorption characteristics for waves incident normally. This provides security and/or isolation for 5 GHz WLAN systems. It passes cellular phone signals and blocks 5 GHz signals by absorbing, as opposed to reflecting. However, its absorption performance is not stable when TE waves are incident at oblique angles (i.e. perpendicular polarisation). The frequency of maximum attenuation changes by more than 8% when the angle of incidence increases from 0 to 45 degrees. The resonance frequency instability is mainly due to the larger inter-element spacing and the larger dimensions of the the unit-cell cross-dipole at 5 GHz [1].

The second absorb/transmit FSS design also provides security for 5 GHz WLAN systems while passing cellular phone signals. This FSS is also a dual-layer structure, with conducting cross-dipoles on one layer and resistive cross-dipoles on the second layer. The advantages of the design are: (1) it provides absorption in the 5 GHz band; (2) it maintains transmission of 900/1800/1900 MHz mobile phone bands; (3) the frequency of maximum attenuation remains relatively stable for different incident angles; and (4) it is more compact than conventional designs making it more practical for commercial use. These properties give the absorb/transmit FSS a clear advantage over conventional Salisbury and Jaumann absorbers, which typically can provide good absorption in the stopband but have poor out-of-band transmission. In this absorb/transmit FSS design, the frequency stability of both polarisations has been achieved by three techniques. Firstly, the inter-element spacing between cross-dipoles has been reduced [1]. This improves the frequency response for oblique angles and has added considerable stability for both polarisations. Secondly, a small circular aperture has been etched at the centre of the conducting cross-dipole to change its surface impedance [103]. For a thin surface, the total electric field on the surface is equal to the product of the surface impedance and the surface current density, which can be represented as:

$$\overrightarrow{E}^{inc} + \overrightarrow{E}^{scat} = Z_s \overrightarrow{J_s} \tag{3.1}$$

where Z_s is the surface impedance. The two limiting cases in this equation occur when $Z_s = 0$ or when Z_s approaches infinity. The boundary condition enforced by the equation is a perfect electric conductor (PEC) when $Z_s = 0$. On the other hand, if Z_s approaches infinity the surface currents are forced to zero and hence no energy is scattered from the surface. In the cross-dipole case, the open-circuit condition is approximated because removing a patch from the centre of the cross-dipole increases the surface impedance [103]. Thirdly, the conducting cross dipoles have been sandwiched between two dielectric layers to provide extra frequency stability and power handling [1].

After discussing both FSS designs, comprehensive theoretical and experimental results for normal and oblique angle transmission and reflection are presented. Results are also presented for a structure without the resistive cross-dipole layer to investigate the contribution of the resistive layer to the absorber. To highlight the frequency-stability improvement of the second FSS design, the results are compared with the first FSS design.

The research presented in this chapter has been published as shown below:

Journal Papers

1. **Ghaffer I. Kiani**, Kenneth L. Ford, Karu P. Esselle, Andrew Weily, and Chinthana Panagamuwa, "*Angle and Polarization Independent Bandstop Frequency Selective Surface for Indoor Wireless Systems*", Microwave and Optical Technology Letters, Volume 50, Issue 9, September 2008, Pages: 2315-2317.

2. **Ghaffer I. Kiani**, Kenneth L. Ford, Karu P. Esselle, Andrew Weily, and Chinthana Panagamuwa, "*Oblique Incidence Performance of a Novel Frequency*

Selective Surface Absorber", IEEE Transactions on Antennas and Propagation, Volume 55, Issue 10, October 2007, Page(s): 2931-2934.

3. **Ghaffer I. Kiani**, Andrew Weily, and Karu P. Esselle "*A Novel absorb/transmit FSS for Secure Indoor Wireless Networks with reduced Multipath Fading*", IEEE Microwave and Wireless Components Letters,Volume 16, Issue 6, June 2006, Page(s): 378-380.

Conference Paper

1. **Ghaffer I. Kiani**, Andrew Weily, and Karu P. Esselle, "*Frequency Selective Surface Absorber using Resistive Cross-Dipoles*", IEEE Antennas and Propagation Society International Symposium, Albuquerque, New Mexico, USA, 9-14 July 2006, Page(s): 4199-4202.

3.1 Absorb/Transmit FSS: First Design

3.1.1 Configuration

The configuration of the dual-layer absorb/transmit surface is shown in Fig. 3.1. Each FSS layer is printed on a 460×310 mm FR4 sheet with a dielectric constant of 4.4. The bandstop filter characteristics are achieved by incorporating an array of conducting cross-dipoles on one side of one of the FR4 sheet, which has a thickness of 1.6 mm. The dimensions of the cross-dipoles and the periodic spacing are also given in Fig. 3.1. The function of the conventional FSS layer is to act as a reflector for WLAN signals while passing mobile phone signals. Then the absorption characteristics are achieved by placing a second FSS layer consisting of resistive cross-dipoles, approximately 10 mm in front of the conducting FSS layer. This concept follows the principle of the

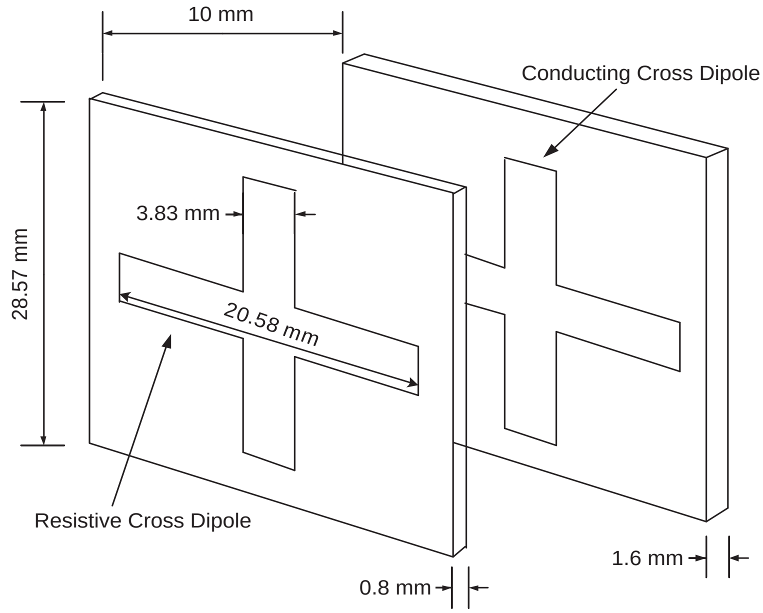

Figure 3.1 Configuration of the dual-layer absorb/transmit surface and dimensions.

conventional Salisbury screen [1], where a uniform resistive sheet is employed for wave absorption. However, unlike in a Salisbury screen, our resistive layer is also a periodic FSS. Its pattern is matched to the first layer, to absorb WLAN signals reflected by the first layer while passing mobile phone signals. The thickness of FR4 used for the resistive layer is chosen as 0.8 mm, and the surface resistance of the resistive dipoles is chosen as 50 Ω per square, as surfaces with these parameters are readily available. The dimensions of the cross-dipoles on both conductive and resistive layers are the same. The FR4 coated with a surface resistive layer was supplied by Ohmega Technologies [104]. Moreover, it should be noted that a conventional bandstop FSS is a single layer structure having periodic conducting elements, while the FSS absorb/transmit designs presented in this chapter have dual-layer structures with the properties described above.

3.1.2 Measurement Setup

Figure 3.2 describes the waveguide measurement technique used to measure the FSS absorber for normal incidence. Two horn antennas from MI Technologies (12-3.9 Standard Gain Horn - SGH) with typical operating frequency of 3.95-5.85 GHz, were used for the measurements. Note that the horn antennas were used at a slightly higher frequency than their specification. Four FR4 sheets with copper on both side were attached together with copper tape to make a waveguide having an aperture of 21.6 cm x 16.0 cm (equals horn antenna aperture). The waveguide simulator was calibrated using a TRL (Through-Reflect-Line) type calibration (open/short/matched load) [105]. The horn from one end of the waveguide was removed to approximate a matched load calibration while the FSS was removed from the waveguide to obtain thru calibration. However, for short circuit calibration a PEC sheet (double sided copper FR4) was added in the waveguide instead of FSS and for the open circuit, the relative position of the PEC sheet with respect to the horn antenna was moved by $\lambda/4$ (12.5 mm at 6 GHz).

3.1.3 Theoretical and Experimental Results

Reflecting FSS

First, the conventional (reflect/transmit type) conducting FSS layer was simulated and designed with the help of Ansoft HFSS software. The theoretical results showed good bandstop transmission and reflection characteristics for the prescribed bands. At 5.25 GHz, the transmission and reflection coefficients are -29.2 dB and -0.3 dB, respectively. The stop band has a -10 dB transmission bandwidth of 620 MHz. At 900 MHz, the transmission and reflection coefficients are -0.1 dB and -17.4 dB, respectively. Around 1800/1900 MHz these coefficients are approximately -0.4 dB and

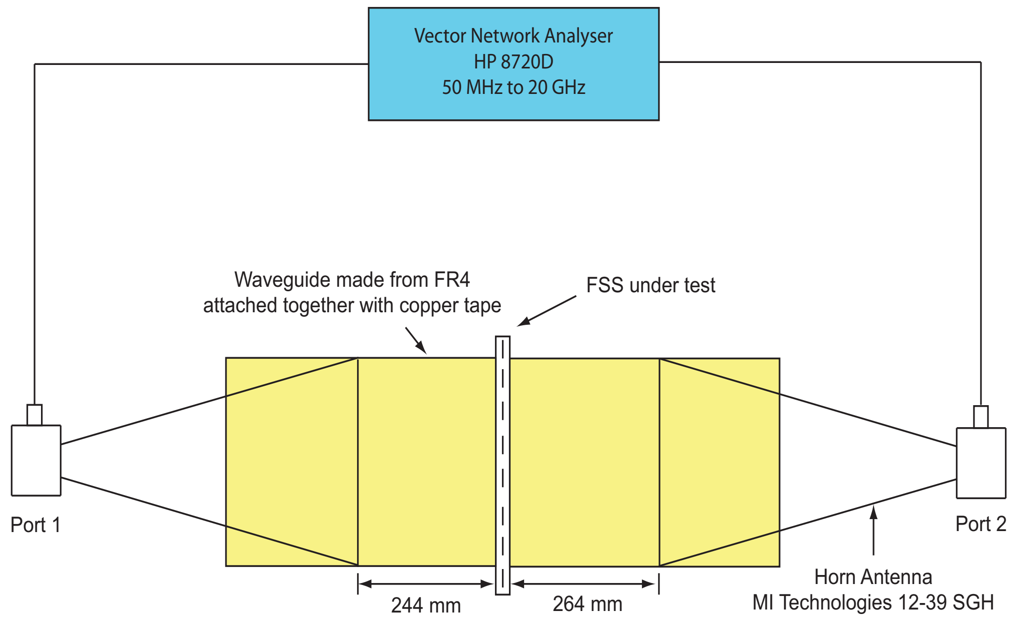

Figure 3.2 Waveguide measurement setup.

-11.3 dB. A prototype was fabricated and experimental testing was carried out using the waveguide technique [106]. The prototype of the FSS absorber is shown in Fig.3.3 while both theoretical and measured results are presented in Fig.3.4. The prototype resonated at 5.37 GHz, giving a transmission coefficient of -22 dB and a reflection coefficient of -0.9 dB. The experimental -10 dB stopband bandwidth is approximately 650 MHz. The measured results compare well with the theoretical results.

Absorb/Transmit FSS With Resistive Cross-Dipoles FSS

The second resistive layer was designed to absorb reflections caused by the first layer at the resonance frequency. The dual-layer FSS was designed using Ansoft HFSS, and the results are shown in Fig.3.5. At 5.25 GHz, the theoretical transmission and reflection coefficients are -37.6 dB and -12.7 dB, respectively. It is worth noting the reduction of WLAN signal reflection by more than 12 dB due to absorption by the resistive FSS layer. The -10 dB transmission bandwidth is now 880 MHz. At 900

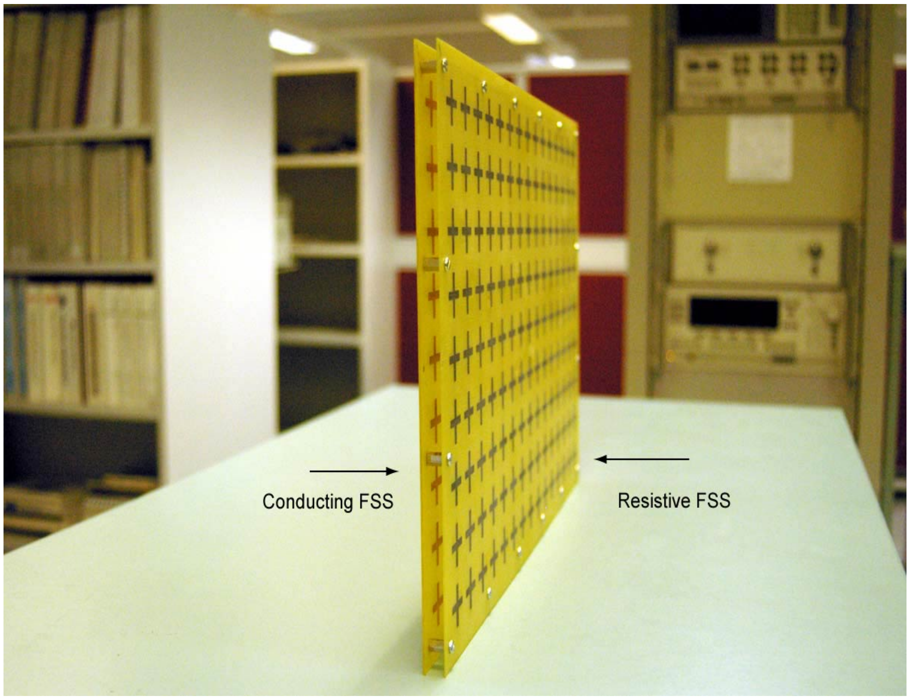

Figure 3.3 The prototype of the FSS absorber.

MHz the transmission and reflection coefficients are -0.1 dB and -17.4 dB, respectively. At 1800/1900 MHz these coefficients are -0.9 dB and -8.8 dB. In short, the second layer did not significantly affect the transmission of mobile phone signals through the structure.

A dual-layer FSS prototype was fabricated and tested using the waveguide technique, from 3.5 to 7 GHz. Its resonance occurred at 5.37 GHz, with a transmission coefficient of -25.2 dB and a reflection coefficient of -10 dB. The measured -10 dB bandwidth is approximately 900 MHz. The measured results are compared with theoretical results in Fig.3.5, and a fairly good agreement can be observed.

Advantage of Resistive FSS

In this section the reason for using a resistive FSS instead of a full 377 Ω per square resistive sheet, for WLAN signal absorption, is elaborated. The scattering parameters

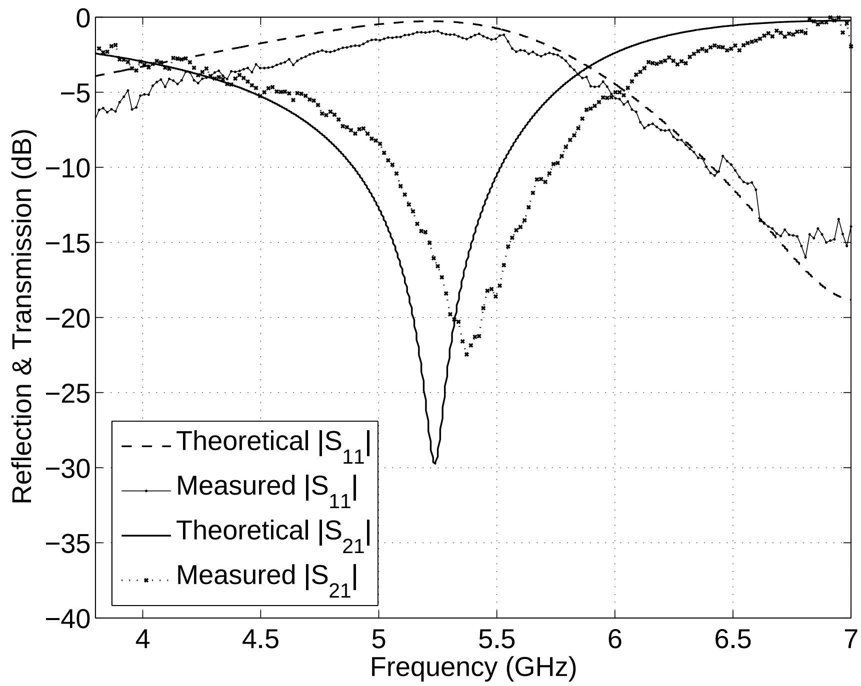

Figure 3.4 Theoretical and measured results of the conventional reflect/transmit conducting FSS layer.

of the novel absorb/transmit dual-layer surface is depicted in Fig.3.6 over a wide frequency range. In this case, good absorption in the bandstop region as well as good transmission in the mobile band is noticeable. On the other hand, when the resistive cross-dipole FSS layer of this structure is replaced by a full 377 Ω per square resistive sheet, a better absorption is achieved in the stopband but the mobile signals are also subjected to attenuation as shown in Fig.3.7. At 900 MHz, the transmission and reflection coefficients, with a 377 Ω per square sheet, are -3 dB and -9 dB, respectively. In contrast, with the 50 square cross-dipole FSS, the transmission and reflection coefficients are -0.1 dB and -17 dB. This comparison shows the advantage of using the resistive cross-dipole FSS over a full 377 Ω per square resistive sheet (e.g., like in a conventional Salisbury screen).

The discrepancy between the theoretical and measured results can be attributed to

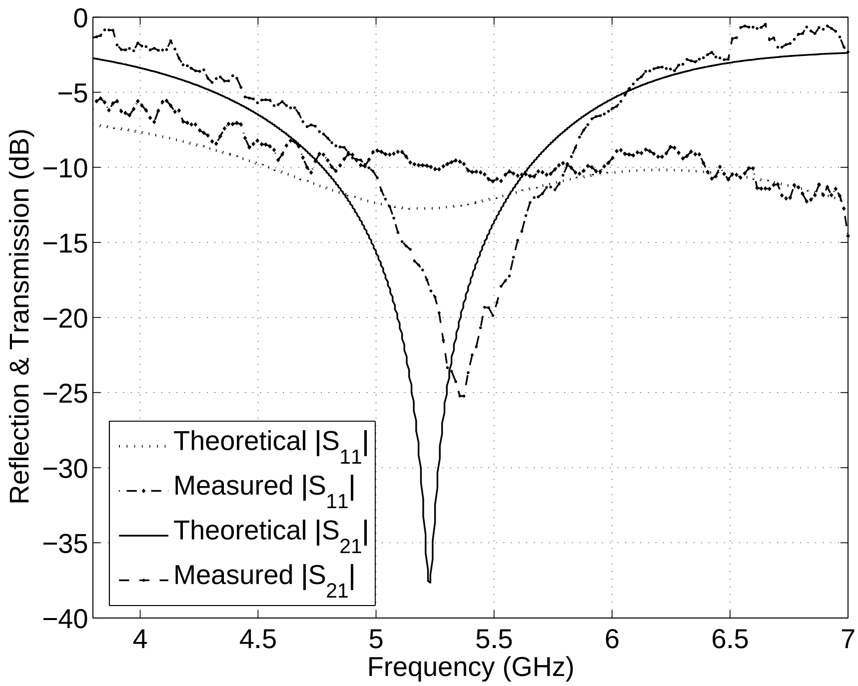

Figure 3.5 Theoretical and measured results of the absorb/transmit surface showing absorption in the stop band.

the variations in the relative permittivity of the substrates used, the tolerances in the fabrication process of the printed circuit board, as well as the mechanical tolerances in the spacing of the resistive and conductive FSS boards (in the case of the FSS with resistive absorber).

Also, we can only have grating lobes if the periodicity is greater than the vacuum wavelength. If the structure is periodic with a period that is smaller than the vacuum wavelength then there are no grating lobes and the only power loss is by heating. If the structure is not perfectly periodic there will be diffuse scattering, i.e, in addition to the transmitted and reflected plane waves there are waves distributed in all directions. In that case power is lost in the diffuse scattering.

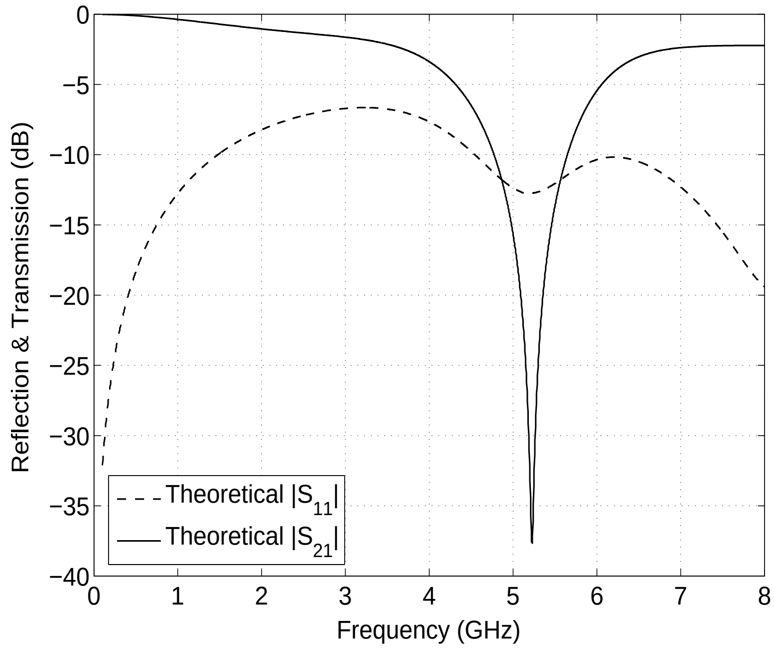

Figure 3.6 Transmission and reflection of the novel absorb/transmit FSS with 50 Ω cross-dipoles on FR4.

3.1.4 Oblique Incidence Instability

In this section the oblique angle performance of the first FSS absorber design, for both perpendicular (TE) and parallel (TM) polarisations, is presented. In the current context the unstable response of FSS means that it is sensitive to incident angles and polarisation states. Figs 3.8 and 3.9 depict the theoretical and measured results for the transmission and reflection properties of an unstable absorb/transmit FSS for perpendicular polarisation at oblique angles (i.e. TE incidence). The original design was completed using Ansoft HFSS, a commercial electromagnetic software package, which predicted resonance at 5.25 GHz for normal incidence. In this case, CST Microwave Studio is used to simulate the absorber for normal and oblique incidence angles. With this software the normal-incidence resonance frequency predicted for the FSS structure is 5.17 GHz.

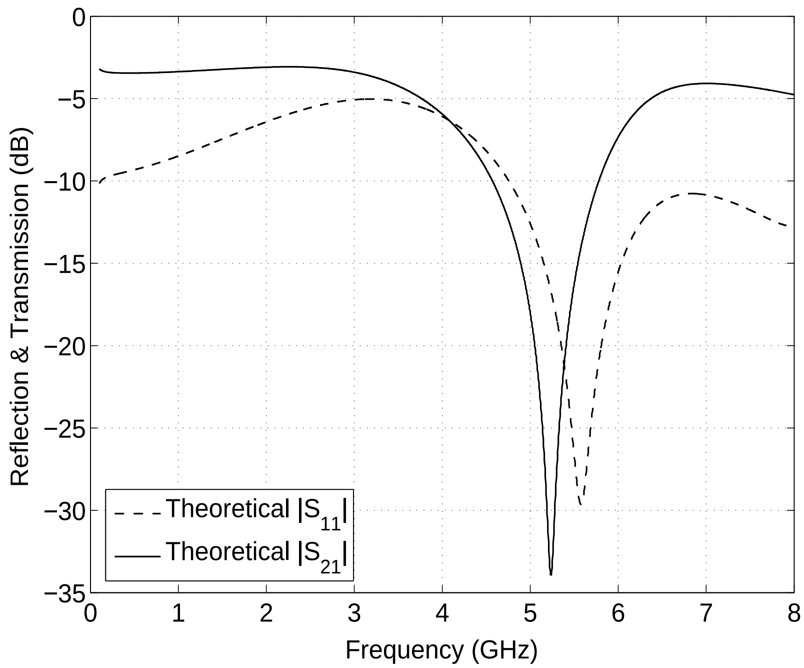

Figure 3.7 Transmission and reflection when the resistive cross-dipole FSS is replaced by a 377 Ω / square resistive sheet, as in a conventional Salisbury screen.

It can be noticed in Fig. 3.8 that a downward shift of resonance frequency occurs as the angle of incidence increases. For 0, 30 and 45 degree angle of TE incidence, the stopband resonance frequencies are 5.17, 4.9 and 4.7 GHz, respectively. The reflection coefficients at each resonance frequency are -13.7 dB, -10.9 dB and -8.8 dB, respectively. The frequency response of this absorb/transmit FSS has been measured and the results are shown in Fig. 3.9. The measured stopband resonance frequencies are 5.44, 5.15 and 4.96 GHz and the reflection coefficients at resonance are -7.6 dB, -7.4 dB and -5.7 dB, for 0, 30 and 45 degrees, respectively.

Measured resonance frequencies are higher than the predicted values, possibly due to variations of the dielectric constant of the FR4 used for FSS fabrication. Other factors affecting the measured resonance frequency include the inaccuracy of the etching method and the measurement setup.

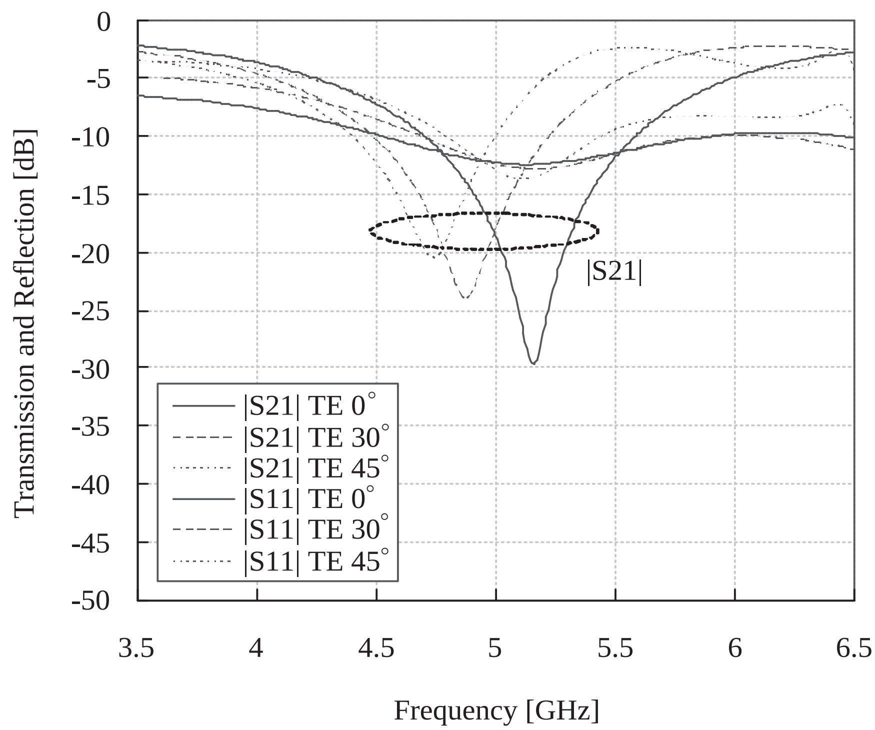

Figure 3.8 Theoretical transmission and reflection of the unstable absorb/transmit dual-layer FSS, at oblique angles, for perpendicular polarisation (TE).

Fig. 3.10 shows the theoretical frequency response of the unstable absorb/transmit FSS for parallel polarisation at oblique angles (i.e. TM incidence). In this case only a small upward frequency shift is noticed as the angle of incidence increases. For 0, 30 and 45 degree angles of incidence, the resonance frequencies are 5.17, 5.20 and 5.23 GHz and the corresponding reflection coefficients are -12.4 dB, -9.5 dB and -6.1 dB, respectively. The frequency response for parallel polarisation was also measured and the results are shown in Fig. 3.11. The resonance frequencies for 0, 30 and 45 degrees are 5.4, 5.44 and 5.4 GHz and the reflection coefficients at resonance are -7.6 dB, -7.4 dB and -5.7 dB, respectively. The transmission coefficient at resonance for all these cases is below -20 dB. Moreover, there is an appreciable reduction in the

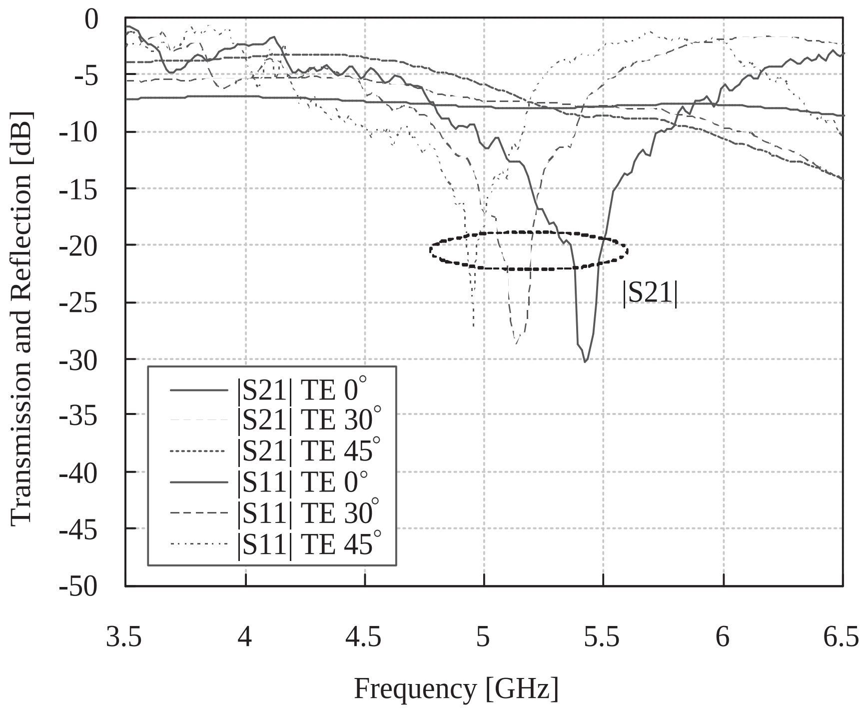

Figure 3.9 Measured transmission and reflection of the unstable absorb/transmit dual-layer FSS, at oblique angles, for perpendicular polarisation (TE).

stopband bandwidth of the absorb/transmit FSS at higher angles of incidence, for both polarisations.

3.1.5 Reason for Unstable Resonance

The electromagnetic/physical description of the FSS is that the structure has resonances that appear at frequencies where the electric and magnetic energies are equal. These resonances occur at discrete frequencies and result in either total reflection or transmission, depending on if it is an aperture FSS or not. It is believed that all periodic structures (with apertures or metallic strips) have resonances for the same reason as systems of coils and capacitors have resonances. In both cases the electromagnetic

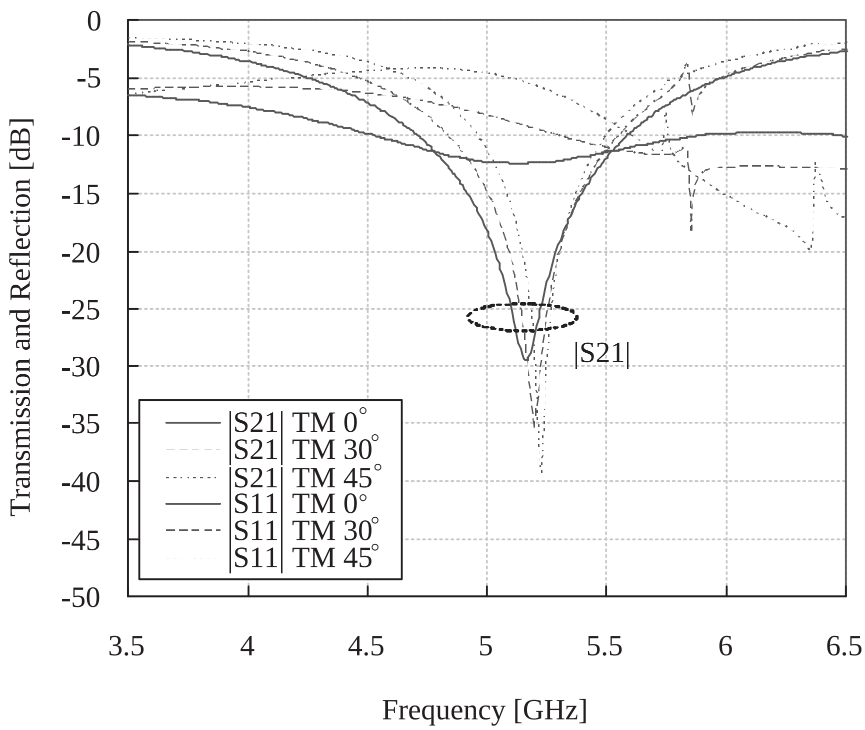

Figure 3.10 Theoretical transmission and reflection of the unstable absorb/transmit dual-layer FSS, at oblique angles, for parallel polarisation (TM).

energy of the system starts at being electric at low frequencies and then become more magnetic as frequency increases (Foster's reactance theorem [107]). When the frequency is increased, a point is reached where the electric and magnetic energies are the same and hence the resonance occurs. Since FSSs are spatial filters and the electromagnetic wave impinging on its surface may strike from different angles (with different polarisations), the impedance of FSS surface changes due to the resolution of E vector into its tangential and normal components and hence the frequency response (as described in Section 2.10) [108] .

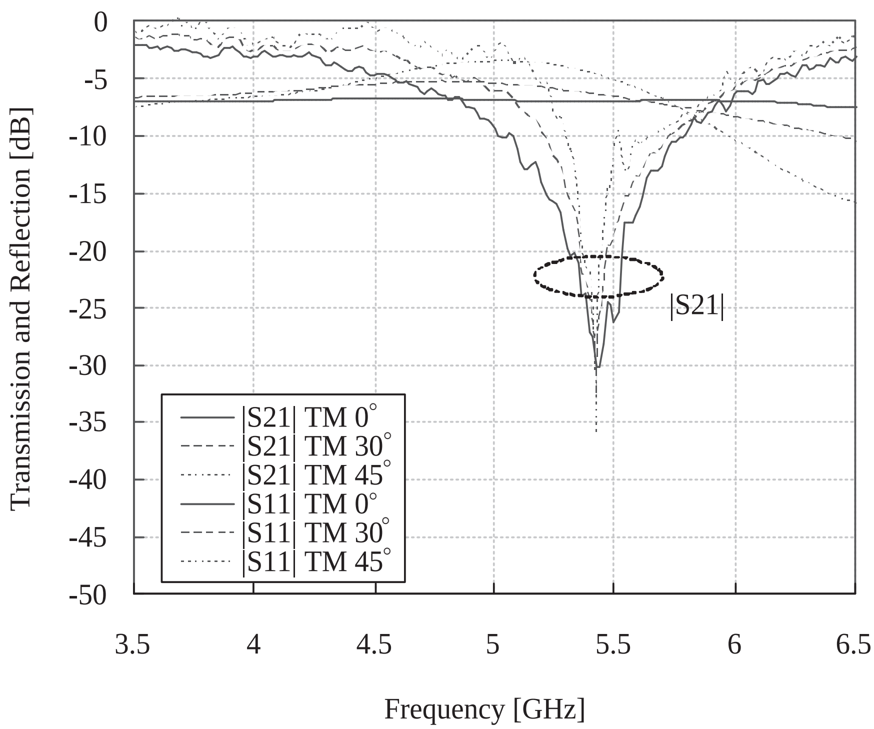

Figure 3.11 Measured transmission and reflection of the unstable absorb/transmit dual-layer FSS, at oblique angles, for parallel polarisation (TM).

3.2 Absorb/Transmit FSS: Second Design

3.2.1 Configuration

The unit cell configuration of this absorb/transmit FSS is shown in Figs 3.12 and 3.13. The 5 GHz bandstop filter characteristics are achieved by incorporating an array of conducting cross-dipoles on one side of one of the FR4 sheets. Another sheet of FR4 with the same dielectric constant and thickness is placed on the open side of the array of conducting dipoles. This sandwiched configuration is shown in Fig. 3.12. The absorption around 5 GHz is achieved by incorporating a layer of resistive cross-dipoles. This two-layer combination operates as an absorb/transmit filter, as follows.

The conducting layer behaves as a conventional reflect/transmit filter, reflecting 5 GHz waves while transmitting mobile phone signals. The "matched" resistive layer absorbs the 5 GHz waves reflected by the conducting layer. The width of the resistive cross-dipoles (2.8 mm) is greater than that of the conducting cross-dipoles (0.6 mm) to obtain good absorption in the stopband. A conjugate matching for the resistive cross-dipoles is not attempted here, since the absorption is comparatively less and resistive sheets with low resistance per square may not be readily available. A circular aperture with a diameter of 0.6 mm has been etched at the centre of both the conducting and resistive cross-dipoles. This aperture makes the design more stable for polarisations at oblique angles of incidence. Each FR4 sheet is 0.8 mm thick, and the surface resistance of the resistive dipoles is chosen as 50 Ω per square, as surfaces with these parameters are readily available.

The stability of the conducting cross-dipole FSS has been enhanced significantly by reducing the inter-element spacing, etching a hole in the centre of the dipole elements and sandwiching the dipoles between two FR4 sheets. If the width of the resistive cross-dipoles were made as narrow as 0.6 mm, this structure would have poor or almost no absorption in the stopband.

The resistive cross-dipole concept follows the principle of the conventional Salisbury screen where a uniform resistive sheet is employed for wave absorption. However, unlike in the Salisbury screen, the resistive layer is also a periodic FSS. Its pattern is matched to the conducting layer in periodicity and shape in order to absorb 5 GHz signals reflected by the conduction layer while passing mobile phone signals. The design has a stable frequency of maximum absorption as well as stable absorption response for both parallel and perpendicular polarisations at oblique angles ranging from 0-45 degrees. The reflection measurements have been carried out in an anechoic chamber at the University of Sheffield, UK, designed to measure oblique angle

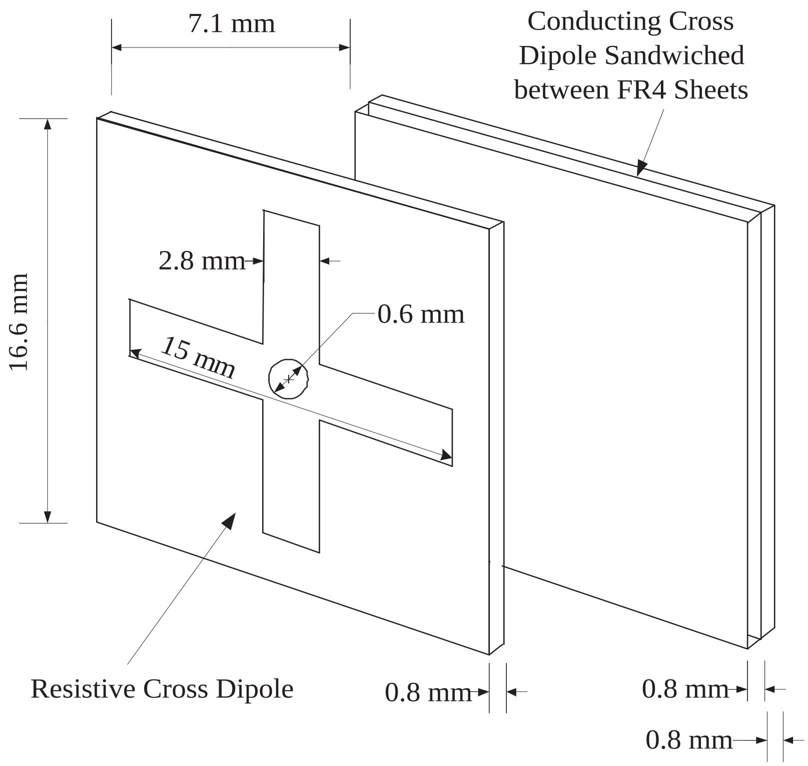

Figure 3.12 The unit cell of the dual-layer absorb/transmit FSS surface with resistive cross-dipoles sandwiched between two FR4 sheets.

performance for both polarisations (refer to Chapter 4, Section 4.5.2). The transmission measurements have been carried out in a testing facility in Loughborough University, UK. This facility is also able to measure the transmission coefficient for both polarisations. The transmission tests were carried out in an anechoic chamber in which the FSS prototype was fitted in a window on a rotatable cardboard sheet. This cardboard sheet was covered with absorber material. The horn antennas were kept on both sides of the cardboard.

3.2.2 Theoretical and Experimental Results

Stable Reflect/Transmit FSS

The conducting FSS layer (i.e. the second layer in Fig. 3.13) is a reflect/transmit

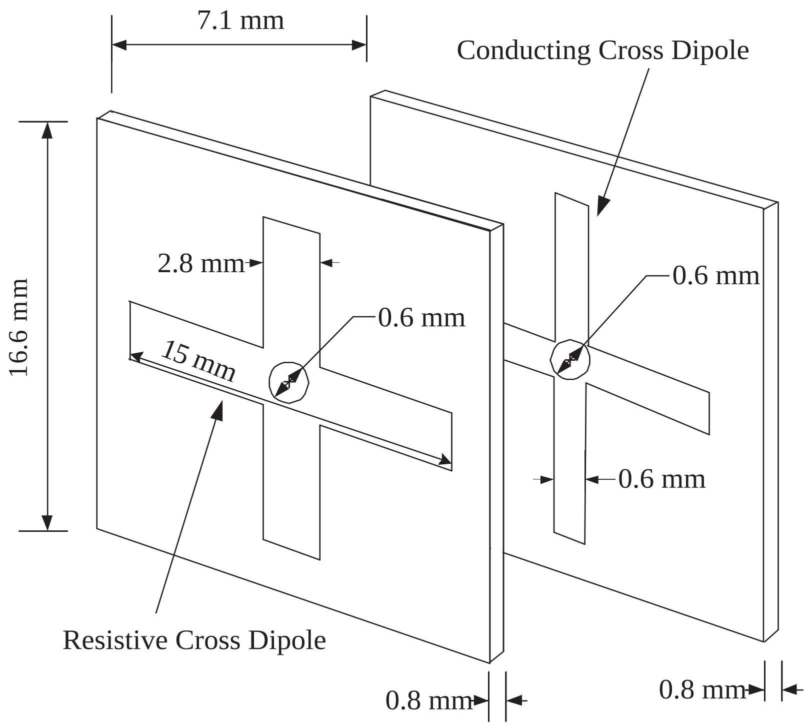

Figure 3.13 The unit cell of the dual-layer absorb/transmit FSS surface. The front FR4 sheet of the conducting cross-dipole has been removed to show its structure more clearly.

FSS with stable performance. Its characteristics (without the absorbing layer) are presented here. The theoretical results have been obtained by CST Microwave Studio and the measurements have been conducted in the same laboratories as previously described.

The theoretical and measured results for perpendicular polarisation (i.e. TE incidence) are presented in Figs 3.14 and 3.15. Fig. 3.14 shows the theoretical oblique angle performance of the new reflect/transmit FSS for perpendicular polarisation. For 0, 30 and 45 degree angles of incidence, the resonance frequencies are 5.28 GHz, 5.28 GHz, and 5.26 GHz and the transmission coefficients are -29.5 dB, -30.4 dB and -32.6 dB, respectively. The reflection coefficient at resonance is almost 0 dB for all angles of incidence considered. The -10 dB bandstop bandwidths for 0, 30 and 45 degree

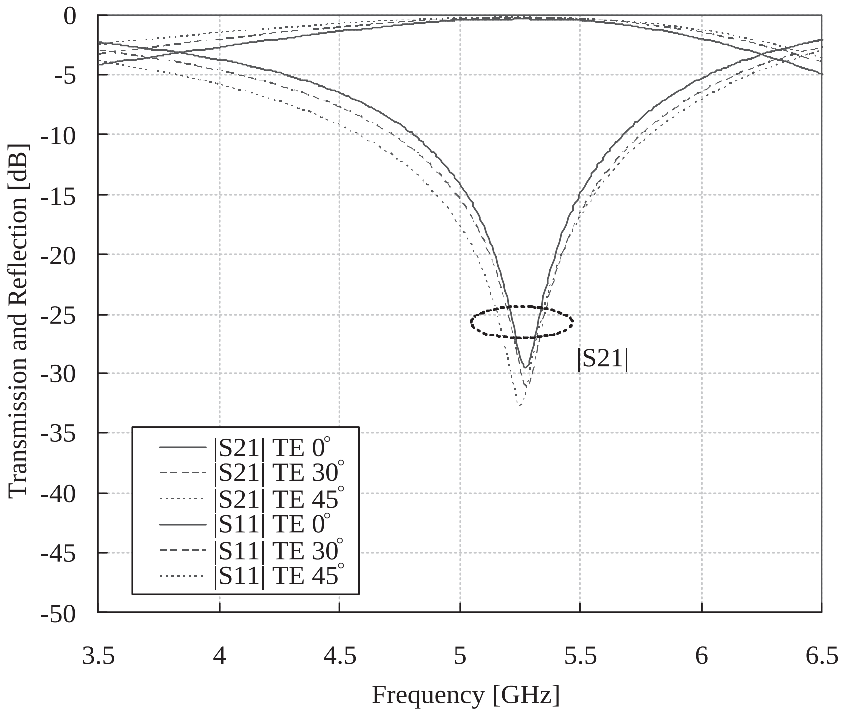

Figure 3.14 Theoretical transmission and reflection of the sandwiched reflect/transmit FSS, at oblique angles, for perpendicular polarisation (TE).

angles of incidence are 1.78 GHz, 2.09 GHz and 2.43 GHz, respectively. Comparing these results with Figs 3.8 and 3.9, we find that this FSS has highly stable resonance frequencies, almost independent of the angle of TE incidence.

A conducting FSS prototype was fabricated and measured, and the results are depicted in Fig. 3.15. For 0, 30 and 45 degree angles of incidence, the resonance frequencies are 5.77 GHz, 5.77 GHz and 5.76 GHz, and the transmission coefficients are -21.4 dB, -24.8 dB and -30.1 dB, respectively. The reflection coefficients in the stopband for all angles of incidence are almost 0 dB. The measured resonance frequency is considerably higher than the theoretical value, and there are two possible reasons for this. In the theoretical model, the dielectric constant was chosen as 4.4 whereas the dielectric constant of the material used for fabrication of the FSS may

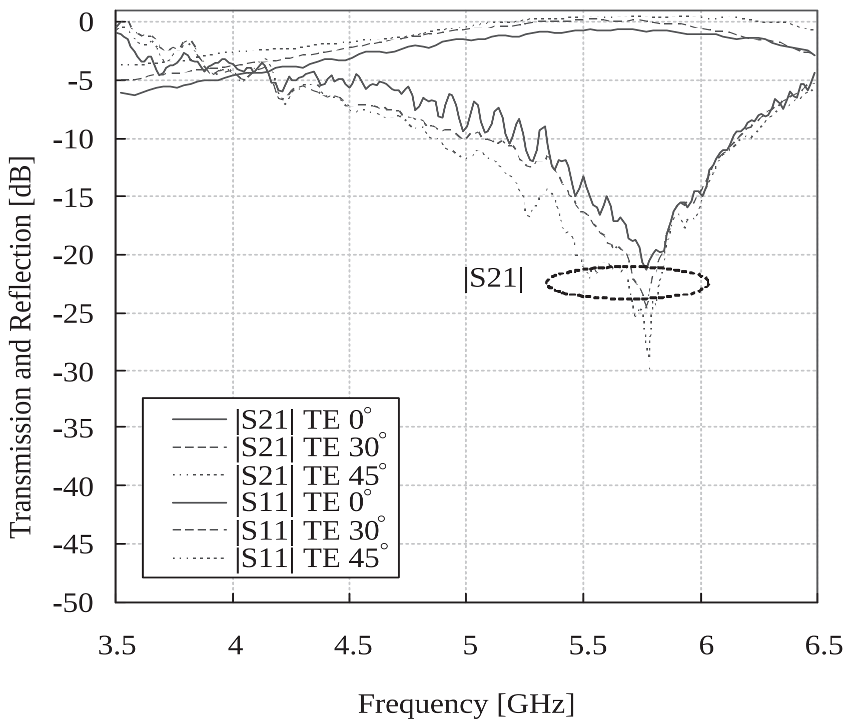

Figure 3.15 Measured transmission and reflection of the sandwiched reflect/transmit FSS, at oblique angles, for perpendicular polarisation (TE).

be smaller than this. The other main reason is the air gap between the two dielectric sheets, which was neglected in the theoretical model. The prototype had approximately 0.032 mm air gap due to the thickness of copper on the dielectric material. Furthermore, ordinary glue was used to bind the sheets together but, due to its uneven binding force, more air gaps are found in the prototype, contributing to the rise in the resonance frequency. The - 10 dB stopband bandwidths for 0, 30 and 45 degree angles of incidence are 1.01 GHz, 1.17 GHz and 1.35 GHz, respectively.

Fig. 3.16 shows the theoretical oblique angle performance of the new reflect /transmit FSS, for parallel polarisation (TM). For 0, 30 and 45 degree angles of incidence, the resonance frequencies are 5.34 GHz, 5.35 GHz, and 5.38 GHz and the transmission coefficients are -28.6 dB, -27.5 dB and -25.2 dB, respectively. The reflection coeffi-

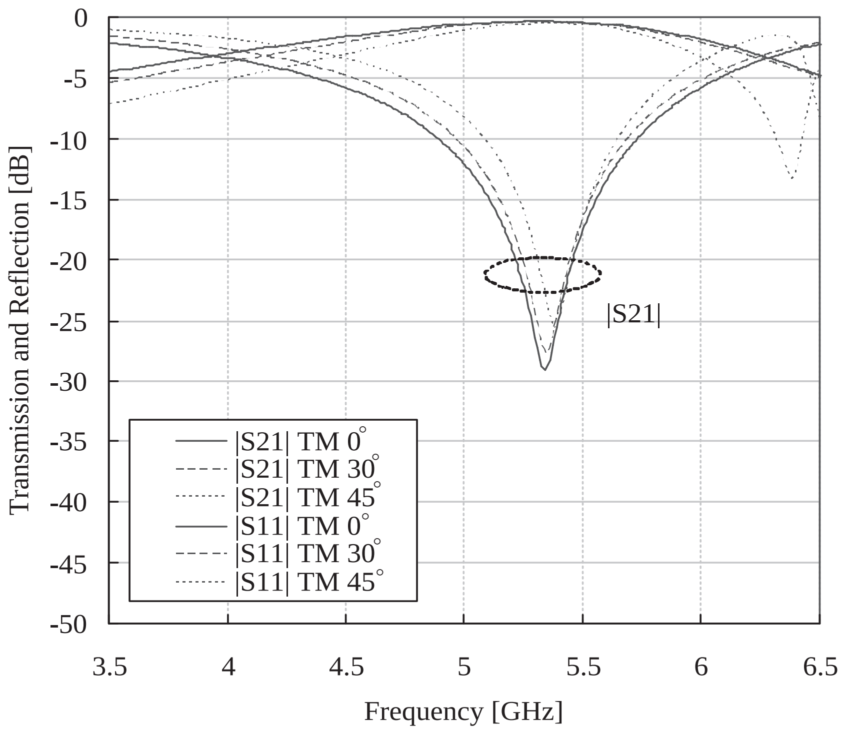

Figure 3.16 Theoretical transmission and reflection of the sandwiched reflect/transmit FSS, at oblique angles, for parallel polarisation (TM).

cient at resonance is almost 0 dB for all angles of incidence. The -10 dB stopband bandwidths for 0, 30 and 45 degree angles of incidence are 1.72 GHz, 1.54 GHz and 0.57 GHz, respectively.

With the increase of the angle of incidence there is a decrease in the stopband width. The measured results for oblique incidence with parallel polarisation (TM) are depicted in Fig. 3.17. For 0, 30 and 45 degree angles of incidence, the resonance frequencies are 5.74 GHz, 5.82 GHz, and 5.89 GHz and the transmission coefficients are -26.6 dB, -23.5 dB and -21.3 dB, respectively. The reflection coefficient at resonance is almost 0 dB for all angles of incidence. The -10 dB bandstop bandwidths for 0, 30 and 45 degree angles of incidence are 0.86 GHz, 0.66 GHz and 0.51 GHz, respectively.

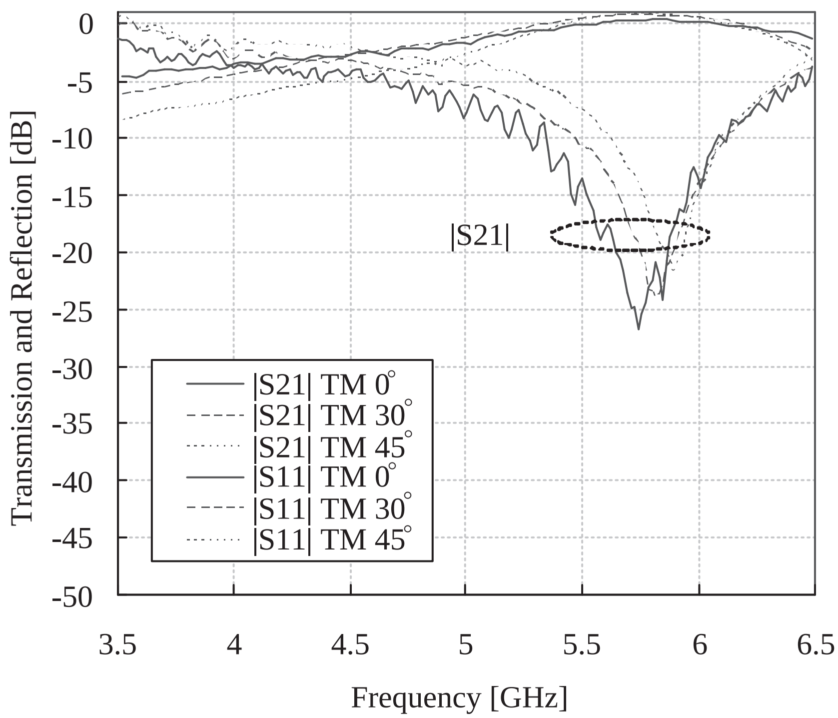

Figure 3.17 Measured transmission and reflection of the sandwiched reflect/transmit FSS, at oblique angles, for parallel polarisation (TM).

Stable Absorb/Transmit FSS

Next, the absorbing layer is added and the two-layer absorb/transmit FSS is formed as shown in Fig. 3.13. The theoretical results of this FSS, for perpendicular polarisation, are shown in Fig. 3.18, while the measured results are depicted in Fig. 3.19.

Due to the addition of the resistive cross-dipole absorbing layer, there is a slight upward shift in the overall resonance frequency of the stopband. The increase in absorption for this case as compared to the previously designed FSS absorber is significant. In Fig. 3.18, for 0, 30 and 45 degree angles of incidence, the resonance frequencies are 5.32 GHz, 5.31 GHz and 5.22 GHz, the transmission coefficients are -44.6 dB, -41 dB and -48.1 dB, and the reflection coefficients at the resonance are

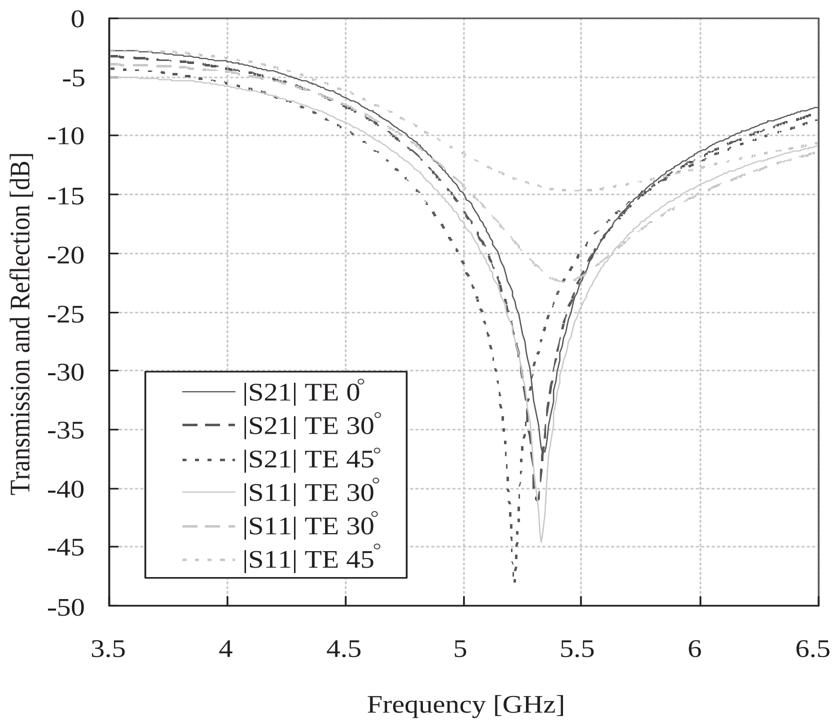

Figure 3.18 Theoretical transmission and reflection of the absorb/transmit FSS at oblique angles, for perpendicular polarisation (TE).

-37.19 dB, -21.44 dB and -13.6 dB, respectively. The -10 dB stopband bandwidths for 0, 30 and 45 degree incidence angles are 1.54 GHz, 1.54 GHz and 1.75 GHz, respectively.

In Fig. 3.19, the measured results of the absorb/transmit FSS at oblique angles are presented for perpendicular polarisation. Once again a higher resonance frequency is observed due to the air gap (Rogers Adhesive was used to sandwich FSS between two dielectric sheets by keeping it under high pressure but air gaps were still expected) and possibly a lower dielectric constant of the FR4 used for the fabrication. For 0, 30 and 45 degree angles of incidence, the resonance frequencies are 5.66 GHz, 5.67 GHz and 5.68 GHz, the transmission coefficients are -25.1 dB, -23.6 dB and -20.9 dB and the reflection coefficients are -20.6 dB, -25.2 dB and -15.3 dB, respectively. The -10

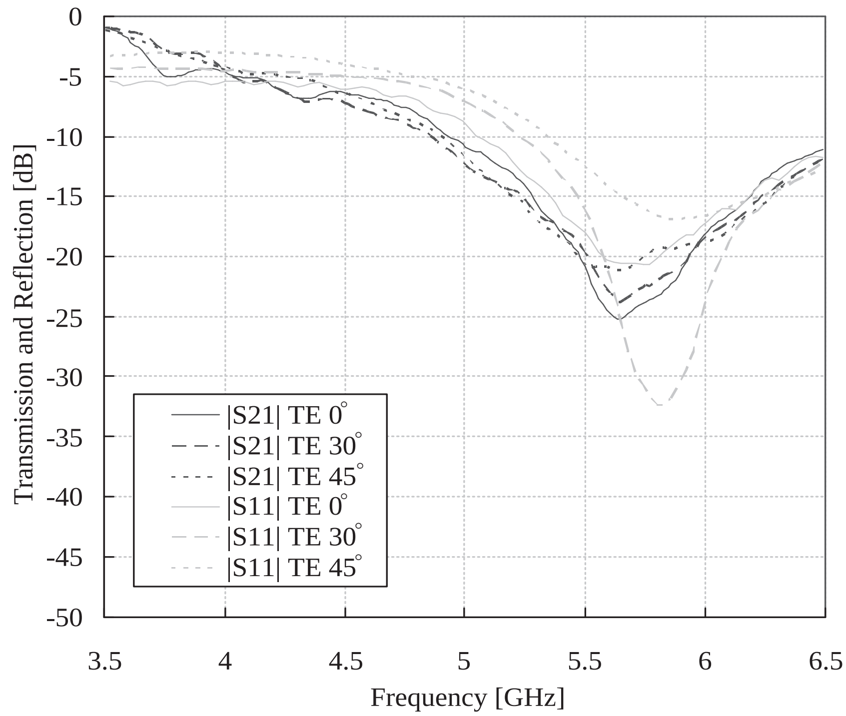

Figure 3.19 Measured transmission and reflection of the absorb/transmit FSS at oblique angles, for perpendicular polarisation (TE).

dB stopband bandwidths for 0, 30 and 45 degree incidence angles are 1.61 GHz, 1.66 GHz and 1.85 GHz, respectively. As predicted in the theoretical results, the frequency of maximum attenuation is very stable with respect to the angle of incidence, even for perpendicular polarisation. The variation of absorption and stopband width agree with the trend predicted in the theoretical results.

Figure 3.20 presents the oblique angle theoretical data of the new absorb/transmit FSS for parallel polarised incident waves. For 0, 30 and 45 degree angles of incidence, the resonance frequencies are 5.32 GHz, 5.32 GHz and 5.38 GHz, the transmission coefficients are -43.2 dB, -33.7 dB and -28.6 dB, and the reflection coefficients are -36.7 dB, -16.9 dB and -9.4 dB, respectively. The -10 dB stopband bandwidth for 0, 30 and 45 degree incidence angles are 1.88 GHz, 1.12 GHz and 0.75 GHz, respectively.

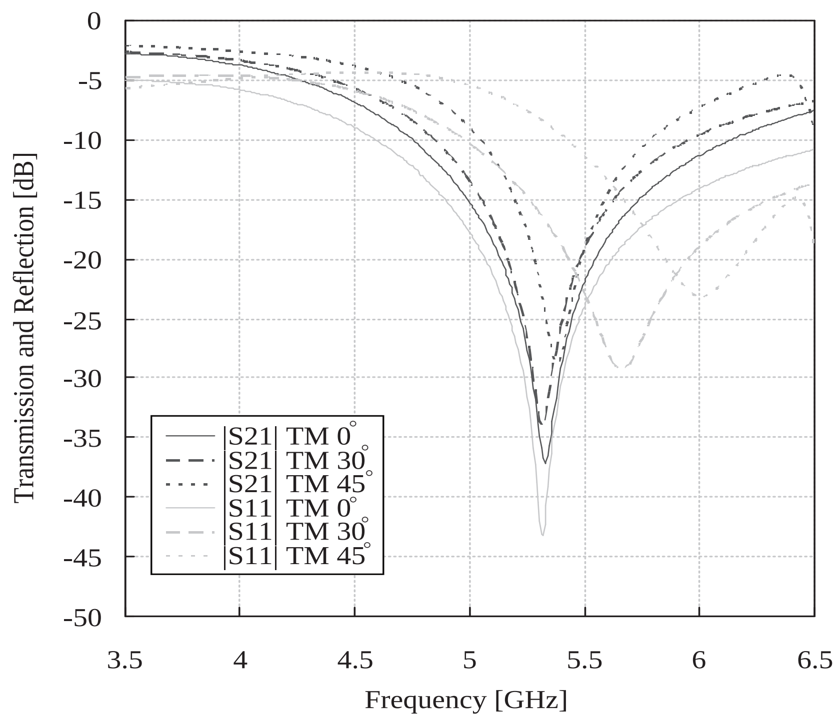

Figure 3.20 Theoretical transmission and reflection of the absorb/transmit FSS, at oblique angles, for parallel polarisation (TM).

There is a decrease in the bandwidth with the increase of the angle of incidence. However good frequency stability and absorption characteristics have been achieved in this case as well.

In Fig. 3.21, the measured data at oblique angles for parallel polarisation are presented. For 0, 30 and 45 degree angles of incidence, the resonance frequencies are 5.7 GHz, 5.8 GHz and 5.9 GHz, the transmission coefficients are -30.8 dB, -21.5 dB and -17.8 dB, the reflection coefficients are -18.8 dB, -14.5 dB and -7.7 dB, and the -10 dB stopband bandwidths are 1.3 GHz, 0.9 GHz and 0.6 GHz, respectively. It is interesting to note that the frequency of maximum attenuation does not align with the frequency of minimum reflection, for TM incidence. As a result, the reflection coefficient at the frequency of maximum attenuation is not small as in the TE incidence; nevertheless

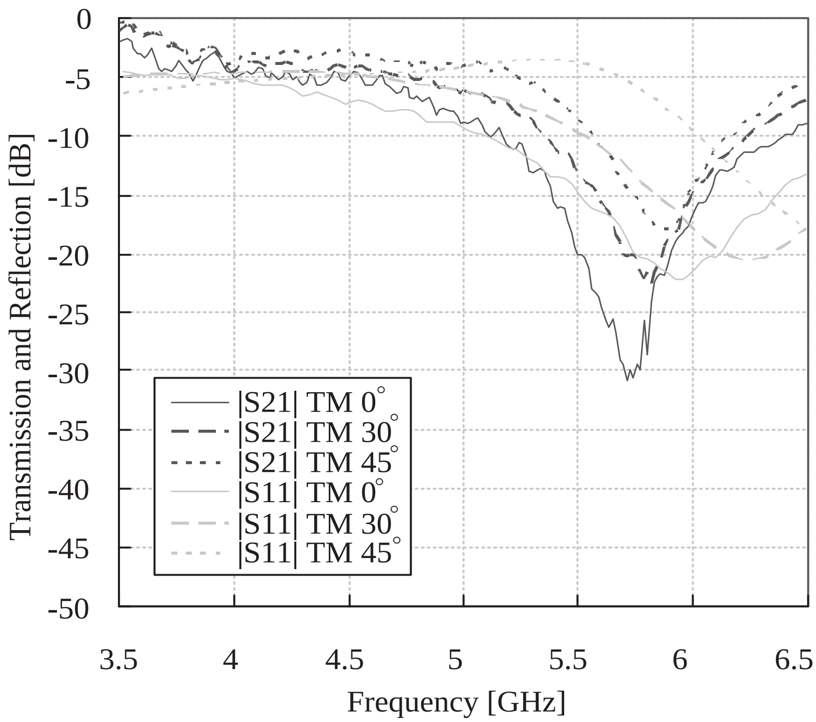

Figure 3.21 Measured transmission and reflection of the absorb/transmit FSS, at oblique angles, for parallel polarisation (TM).

it is less than -7.7 dB for the range of incidence angles considered.

Discussion

In Table 3.1, the theoretical results for the stable and unstable FSS absorbers are compared to give an overview of the improvement in the second FSS design. It is clear from these results that the second design has a stable frequency of maximum attenuation for both TE and TM incident waves, whereas the first FSS design is stable only for TM incident waves. Furthermore, the levels of absorption achieved by the second FSS design are significantly greater than those of the previous design.

The noise in the transmission measurements for oblique angles was due to the small size of the FSS prototypes. Moreover, for measurements at large angles of incidence,

Incident Wave	First Design	Second Design
TE 0°	Resonance = 5.17 GHz	Resonance = 5.32 GHz
	Attenuation = 13.7 dB	Attenuation = 37.2 dB
TE 30°	Resonance = 4.88 GHz	Resonance = 5.31 GHz
	Variation = - 5.6 %	Variation = - 0.2 %
	Attenuation = 11.0 dB	Attenuation = 21.4 dB
TE 45°	Resonance = 4.74 GHz	Resonance = 5.22 GHz
	Variation = - 8.3 %	Variation = - 1.8 %
	Attenuation = 8.8 dB	Attenuation = 13.6 dB
TM 0°	Resonance = 5.17 GHz	Resonance = 5.32 GHz
	Attenuation = 12.4 dB	Attenuation = 36.7 dB
TM 30°	Resonance = 5.20 GHz	Resonance = 5.32 GHz
	Variation = + 0.6 %	Variation = No Change
	Attenuation = 9.5 dB	Attenuation = 16.9 dB
TM 45°	Resonance = 5.23 GHz	Resonance = 5.38 GHz
	Variation = + 1.1 %	Variation = + 1.1 %
	Attenuation = 6.1 dB	Attenuation = 9.7 dB

Table 3.1 Percentage variation in the theoretical frequency of maximum attenuation at normal and oblique angles for both TE and TM polarisations.

the small transmission window was slightly shadowed by the surrounding absorbers, leading to additional noise in the measured data. Therefore, for the absorb/transmit FSS measured data, averaging has been applied for 45^o to smooth the transmission curves. As discussed earlier, the measured resonance frequencies sometimes differ from theoretical resonance frequencies. This was due to: (a) the air gap between the two dielectric sheets sandwiching the conducting cross-dipoles; (b) a sag in both layers of absorbers due to their smaller thickness, causing poor mechanical strength; and (c) the use of 7.1 mm spacers only at the edges of the conducting and resistive FSS layers causing non-uniform spacing between the sides and the centre.

3.3 Transmission of useful Signals

In Fig. 3.22, it can be noticed that the frequency bands such as GSM 900/1800/1900 etc. have good transmission through the new absorb/transmit FSS. This behavior can not be achieved with conventional Salisbury and Jaumann absorbers in which the out of stopband frequencies are totally attenuated. Moreover, the transmission of useful frequencies does not change much as the angle of incidence is varied from 0 to 45 degrees.

3.4 Production Cost

These types of FSS absorbers may be produced on mass scale without much cost. Both the dielectrics (used in FSS design and fabrication) with copper and resistive material coating, are readily available and not very expensive. For example, a 36×48 inch FR4 sheet is available for about AUD 30, while for a 40×51 inch FR4 sheet with resistive coating is available for about AUD 500. For a mass scale FSS production, the whole sale price may be even cheaper. Standard milling machines used for making Printed Circuit Boards (PCBs) may be used for the etching of FSS.

3.5 Conclusion

3.5.1 Absorb/Transmit FSS: First Design

The novel absorb/transmit FSS with a dual-layer surface provides WLAN security through frequency selective absorption, rather than reflection, and hence does not cause additional multipaths, delay spread, or signal degradation. The resistive FSS layer plays a major role in achieving this performance without significantly attenu-

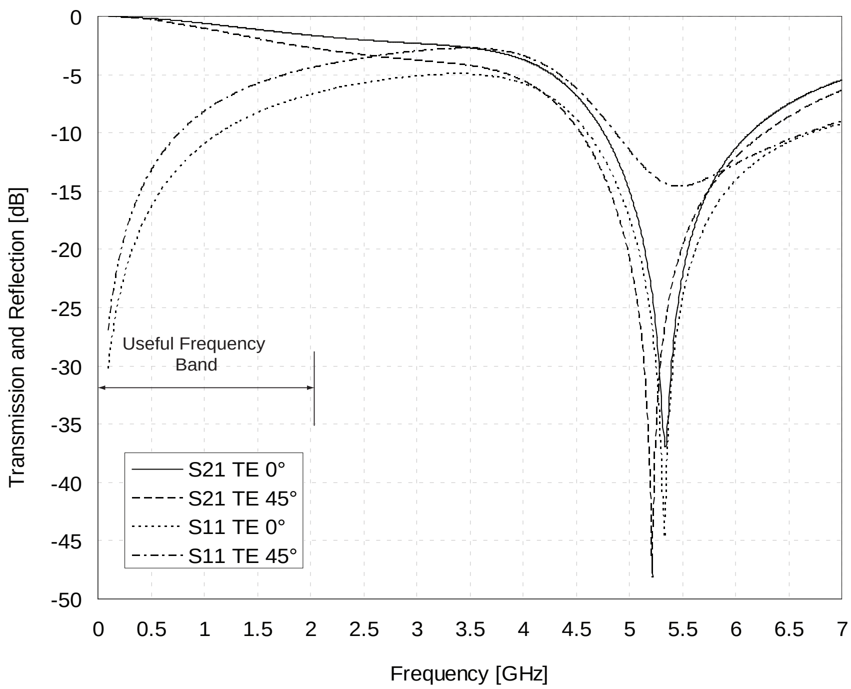

Figure 3.22 Theoretical transmission and reflection of the absorb/transmit FSS, showing the improved transmission of useful frequencies.

ating mobile phone signals. The pattern of the resistive (absorbing) FSS has been matched to that of the conducting (reflecting) FSS such that only WLAN signals reflected by the conducting FSS are significantly absorbed by the absorbing FSS layer. Unlike in a conventional Salisbury screen [1], which has a full resistive sheet, the resistive FSS allows passage of mobile signals almost unattenuated.

This structure can help WLAN providers to a) stop people outside their premises from accessing the service and b) increase service quality and speed by physically dividing the service area into several smaller areas and running independent WLANs in each small area, i.e., reusing channels. Due to the absorption properties, each WLAN area can be made much smaller without creating undesirable multipaths. Another use may be in protecting highly sensitive wireless networks. Due to the absorbing properties of the surface, intruders cannot easily detect that the WLAN is protected. In contrast, a network protected by a reflecting FSS can be easily detected using a low-power microwave transmitter and a detector.

3.5.2 Absorb/Transmit FSS: Second Design

A dual-layer cross-dipole absorb/transmit FSS has been designed, prototyped and tested. Its performance has been demonstrated through both theory and experiments. It showed a stable frequency of maximum attenuation for both polarisations at normal and oblique angles of up to 45 degrees. Its working principle is same as of first absorber design, however good frequency stability of this design ensures that the FSS will absorb signals over a wide range of incidence angles, not only at normal incidence.

The distance between the two FSS layers is of the order of 1/8 of the free-space wavelength, which makes it half as thick as conventional absorbers which have a standard $\lambda_0/4$ distance between the layers. Due to the added advantage of compact size, a third FSS layer similar to the resistive FSS layer can be placed on the other side of the conducting FSS layer at a distance of approximately $\lambda_0/8$ to create a two-way absorber. By adding this second resistive FSS layer, the total distance between the edges of the FSS absorber will still remain close to $\lambda_0/4$ as in the case of other conventional absorbers. This triple-layer absorber can be incorporated in a wall of a building for advanced wireless security in such a way that its bi-directional absorbing characteristics can mislead an intruder.