SYNOPSIS OF

DESIGN AND DEVELOPMENT OF PRINTED PERIODIC STRUCTURES FOR MICROWAVE APPLICATIONS

A THESIS

to be submitted by

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for the award of the degree

of

DOCTOR OF PHILOSOPHY

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November, 2021

1 Introduction

A periodic structure which has frequency filtering properties based on its geometrical and material properties can be termed as a Frequency Selective Surface (FSS). These surfaces have identical elements called unit cell which are arranged periodically in a one or two dimensional array. Based on the dimensions of the element, the array is resonant for a particular frequency. When a plane wave incident on such FSS the resonant frequency is either reflected or transmitted depending on its structure being an array of conductive patch or slot elements, respectively.

With advancements in wireless communication, FSS were adopted in antenna system design to function as hybrid radomes, dichroic reflectors, EM absorber, polarization converter, EM shield, gain enhancer, spatial filter etc. An efficient FSS is expected to have polarization independence, delayed onset of grating lobes, angular and conformal stability. Unit cell miniaturization is an excellent design solution to achieve these properties. Prominent ways of achieving cell miniaturization include (i) design of combination type unit cell (ii) multi-layered model (iii) SIW approach (iv) Use of active/passive surface mount components (v) 3D structures. Due to its ease of manufacturing the combination/hybrid type unit cell technique is mostly preferred to develop high performing FSS. However, the design of such miniaturized cell structures which enhance FSS performance is greatly challenging.

The main objective of the thesis is to introduce various design methodologies which can develop efficient and frequency scalable miniaturized FSS for various functionalities. Each FSS design presented in the thesis involves detailed structural, parametric and circuit analysis along with experimental results for practical validation.

1.1 Literature Review

The following sub-sections provide a brief literature review on miniaturized FSS components such as reflectors, absorbers and polarizers with hybrid cell structures. It also highlights the current challenges in designing efficient FSS components for various applications. The latter part of the thesis introduces the use of additive manufacturing(AM) for FSS prototyping which could overcome several complexities faced with standard PCB manufacturing.

1.1.1 FSS based reflectors

There are various structural design techniques to achieve single-layered dual-band FSS reflector. However, designing such reflectors to operate at specific frequencies with a highly miniaturized unit cell is a challenge. Design approaches like convoluted structure [1], close loop structure [2], meandered center-connected structure [3] and fractal structures [4] have been proposed for dual-band FSS reflectors. The level of miniaturization varied from 68.3% to 93.6% and the lowest resonant frequency was reported at 2.3 GHz. This clearly shows the design challenge of obtaining miniaturized FSS reflector at lower frequency of operation.

Wideband FSS reflectors with fractional bandwidth (FBW) ranging from 43.7% to 121.6% were achieved by employing various design techniques like: combination cell type FSS [5,6], dual-side printed FSS [7,8], FSS with vias [9], FSS with modified loop element [10] and FSS with on-board diodes [11]. However, a deeper survey of these reflectors highlights the need for miniaturized ultrawideband reflectors with high angular stability and low f_L (lower cut-off frequency).

The design of a multi-band antenna system for satellite communication is very economical as its multi-band operability significantly reduces the systems mass and volume. A multi-polarized antenna system along with a polarization sensitive reflector [12–14] can provide an additional benefit of polarization selectivity. Thus, designing a proper multi-band, polarization sensitive sub-reflector can boost the antenna performance and make it economically viable.

1.1.2 FSS based absorbers

The use of metamaterial (MTM) design approach for planar FSS absorbers [15] led to a new class of absorbers which could have multi-band operability with absorber thickness as low as 0.011λ. The MTM type FSS absorbers could also mitigate the issues regarding angular instability and polarization sensitivity. Several single band, dual-band, multi-band [16–18] and wideband absorbers have been designed using the planar MTM approach. However, the reported multi-band absorbers with closely spaced absorptive bands were not as compact as the absorbers with distantly spaced absorptive bands.

1.1.3 FSS based polarizers

A polarization transformer like FSS polarizer is a key aspect of circularly polarized wave systems which have better channel performance as they mitigate polarization mismatch, multi-path fading, atmospheric absorptions and reflections. A transmissive type polarizer is preferred over a reflective one as it can avoid blockage loss. Anisotropy induced in conventional FSS structures produced polarization conversion at a single narrow band [19]. Dual-side printed structures were proposed to obtain a wider polarization transformation bandwidth [20, 21]. Combinational type cell structures [22, 23] and cascaded structures [24–26] were other approaches used to obtain wide bandwidth. While these design approaches solved the bandwidth limitation to a good extent the next awaiting challenge was multi-band polarization conversion. Compact multi-band polarizers with thickness as low as 0.007λ and FBW of around 20% could be achieved with dual-side printed combinational cell structures [27]. While single side printed polarizer FSS [28] could generate FBW close to 20%, it suffered a trade-off in terms of compactness.

1.2 Key contributions of the thesis

The key contributions of the thesis are as follows:

- A dual-band FSS reflector which is highly miniaturized due to its orthogonally meandered open loop structure is proposed for S-band applications. It operates at 1.23 and 3.3 GHz and has a compact unit cell dimensions are $0.033\lambda_0 \times 0.033\lambda_0 \times 0.003\lambda_0$, where λ_0 stands for free space wavelength at the lower resonating frequency. The reflector is also angularly stable and polarization independent.

- An FSS reflector is modelled for ultrawideband operation and has its stop band frequency ranging from 1.01 to 9.84 GHz. A novel cell-interconnected open loop structure with coupling mechanism ensures a sub-wavelength unit cell dimension of $0.04\lambda_0 \times 0.04\lambda_0 \times 0.0027\lambda_0$. The wideband reflector with an FBW of 162.8% has stable response for oblique incidence angles and orthogonal polarizations.

- A low-profile quad-band FSS designed as a sub-reflector for satellite communication has center frequencies at 4.6, 5.5, 6.3 and 7.3 GHz with an average bandwidth of 240 MHz. The unit cell has miniaturized dimension of $0.138\lambda_0 \times 0.138\lambda_0 \times 0.012\lambda_0$. This single layered FSS reflector employs non-concentric open loops with controlled field coupling to provide four closely spaced transmission zeroes within the C-band. This angularly stable FSS can be mechanically tuned to reflect either TE or TM polarized waves.

- An ultrathin, metamaterial-based quad-band absorber demonstrates distinct absorptivity peaks of 99.5, 98.1, 98.6 and 99.8% at 4.38, 5.68, 6.86 and 7.6 GHz respectively. The novel edge interconnected cell structure ensures unity frequency ratio between adjacent peaks. The absorber has a thickness of $0.011\lambda_0$ and cell dimension of $0.217\lambda_0 \times 0.217\lambda_0$. The polarization independent absorber exhibits angularly stable frequency response for oblique incident angles upto 45°

- An ultrathin, single layered and one side printed FSS polarizer is proposed for polarization conversion from linear to circular in S-band frequency. It has a compact unit cell dimensions of $0.075\lambda_0 \times 0.075\lambda_0$ and model thickness of $0.005\lambda_0$. It has dual-sense polarization conversion i.e., converts linearly polarized (LP) EM waves of frequency ranges 2.06 to 2.6 GHz and 3.37 to 3.77 GHz into left-hand circularly polarized (LHCP) and right-hand circularly polarized (RHCP) EM waves, respectively. It exhibits stable frequency response for a wide scan angle ranging from +30° to -30°

- A 3D all-dielectric FSS reflector is proposed for high power applications in the Ku-band. It has a bandwidth of with 700 MHz centered around the operating frequency of 15 GHz. It has good roll-off rate with two transmission zeroes at 14.85 and 15.19 GHz. The structure which has hexagonal projections from a flat surface is additively manufactured using thermoplastic polyurethane (TPU) material. The FSS which has good conformability due to the flexible TPU material exhibits a stable frequency response for orthogonal polarizations.

- The advantages of adapting AM over PCB manufacturing for FSS prototyping, are demonstrated by critically analysing an additively manufactured FSS reflector and antenna.

- All the FSS presented in this thesis have been represented with an equivalent circuit model and validated with simulations and measurements.

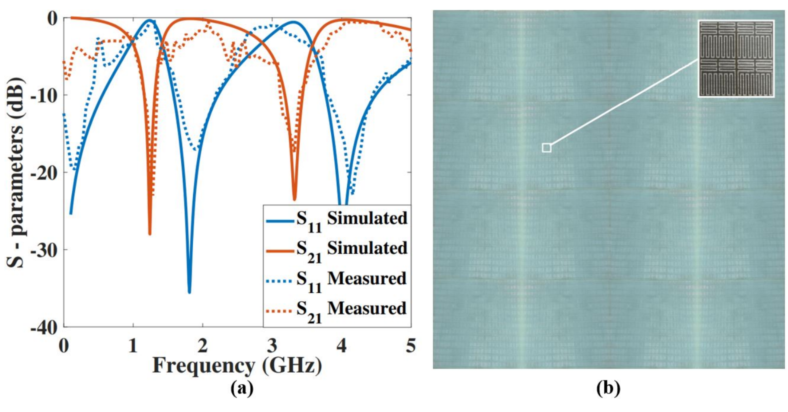


Figure 1: (a)Measured and simulated FSS characteristics (b)Fabricated FSS prototype.

2 Design of FSS Based Microwave Reflectors

2.1 Dual-band miniaturized FSS reflector

The frequency response of the proposed dual-band FSS reflector is verified by experimental validation of a fabricated prototype which has an array of 56×56 unit cells. Fig. 1(a) shows the simulated and measured results of the FSS at normal incidence. It can be noted that the reported FSS resonates at 1.23 and 3.3 GHz with a fractional bandwidth of 32.5% and 18.2%, respectively. A photograph of the fabricated FSS is shown in Fig. 1(b). The developed FSS is angularly stable due to its compactness. Even though the unit cell exhibits only dyad symmetry, the FSS is polarization independent due to extremely small size of the unit cell for the given operating frequency.

2.2 Wide-band miniaturised FSS reflector

To validate the frequency response of the proposed wide-band FSS reflector, the proposed FSS with 300×300 mm^2 dimension is fabricated and measured with the setup shown in Fig. 2(a). The simulated and measured results are shown in Fig. 2(b). The measured results are plotted from 1 GHz, as the antennas used in the measurement setup have been pre-calibrated for the range of 1 to 18 GHz. The -10 dB FBW remains the same in case of measured result, thus proving the wideband characteristics of the prototype. The reported FSS is also angularly stable and polarization independent up to 45° due to its compact and symmetric structure.

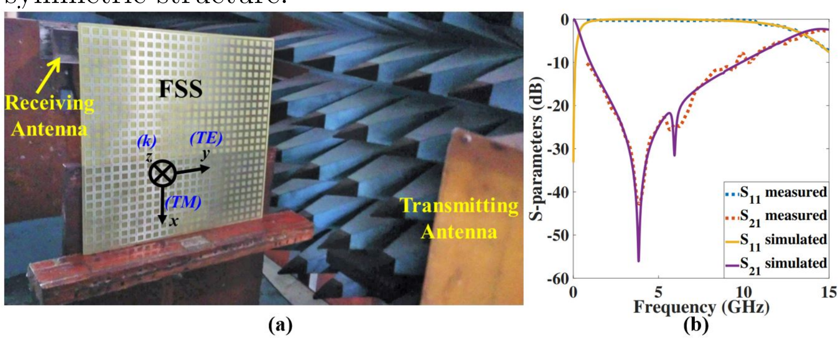


Figure 2: (a)Measurement setup to determine S_{21} (b)Wide-band FSS Characteristics.

2.3 Multi-band miniaturised FSS reflector

The presented quad-band FSS is simulated using Ansys HFSS with periodic boundary conditions and floquet port analysis. The prototype is fabricated on a 297×297 mm^2 substrate to accommodate 33×33 unit cells. The measurement setup used to obtain S_{21} of the FSS for normal incidence is shown in Fig. 3(a). The frequency response is noted from Keysight E5071C VNA. The measured versus full-wave simulated response is plotted in Fig. 3(b). The miniaturized quad-band FSS also renders angular stability up to 45°. The designed FSS is mechanically rotated to be polarization selective. In reference position (1) as shown in the inset of Fig. 3(a) the FSS reflects all the four desired bands when they are TE polarized but allows them when TM polarized. By rotating the FSS along its propagation axis by 90°, the FSS reflects the four bands in TM polarized condition but, allows them in TE polarized condition. This verifies the polarization selective behaviour of the proposed FSS.

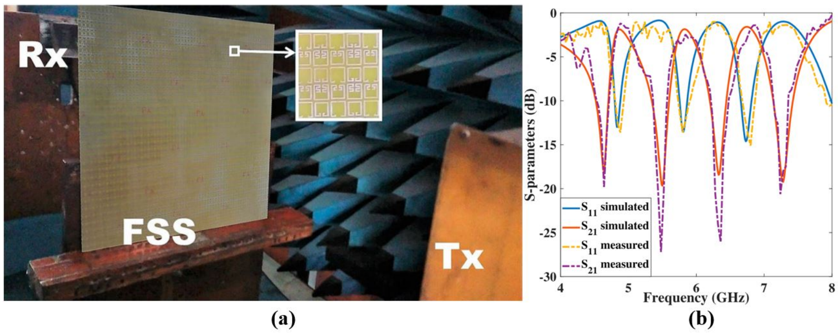


Figure 3: (a)Measurement setup to determine S_{21} (b)Multi-band FSS Characteristics.

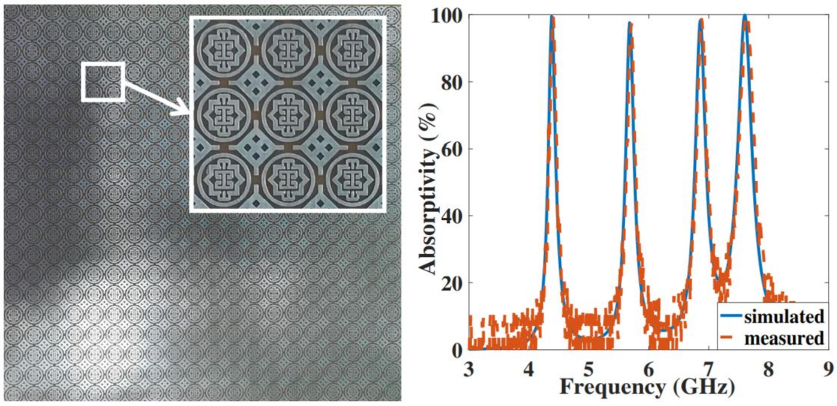
2.4 Summary

Firstly, a dual-band FSS reflector designed with a miniaturized unit cell and single substrate layer is introduced. Its design methodology based on a fusion of conventional meandering and a novel open loop ideology allows it to operate in the lower frequency band at 1.23 and 3.3 GHz. The miniaturization achieved is evident from its unit cell dimension which is $0.033\lambda_0 \times 0.033\lambda_0 \times 0.003\lambda_0$ where λ_0 stands for the free space wavelength at the lower resonating frequency. Secondly, a single layered, dual side printed wide stop-band FSS is presented. The unit cell structure is based on a cascaded combination of loop-type and cell interconnected structures. This wideband FSS functions effectively for an FBW of 162.8% with its -10 dB bandwidth ranging from 1.01 to 9.84 GHz. Its compact and symmetric structure is distinguished by a unit cell dimension of $0.04\lambda_0\times$ $0.04\lambda_0\times$ $0.0027\lambda_0$. Both these reflectors are angularly stable and polarization independent. Finally, a polarization selective and angularly stable quad-band FSS reflector is discussed. The proposed structure with four distinct open loops provides four closely spaced nearly equal narrow bands centered at 4.6, 5.5, 6.3 and 7.3 GHz. The frequency ratio between adjacent transmission zeros is close to unity and the average bandwidth is 240 MHz. The single layered FSS reflectors proposed in this section are cost effective and easy to manufacture. Moreover, due to their single layered structures these reflectors have better design flexibility and frequency scalability to any practical microwave application.

3 Design of FSS Based Microwave Absorber

The proposed absorber is fabricated with a sheet dimension of 300×300 mm^2 as shown in Fig. 4(a) for experimental validation. The simulated and measured values plotted in Fig. 4(b) show good concordance. The reported absorber is angularly stable and polarization independent up to 45° due to its miniaturized and four-fold symmetric structure. The ultra-thin MTM absorber shown here has absorptivities of 99.5, 98.1, 98.6 and 99.8%

for four well-defined frequencies of 4.38, 5.68, 6.86 and 7.6 GHz, respectively. The four-element structure with one element divided at the edges provides a compact cell size. It also ensures that the frequency ratios between the adjacent peaks are maintained close to unity, to accommodate four definite bands within the C- band. The single layered element design provides the structural robustness to tune to any desired frequency with ease.

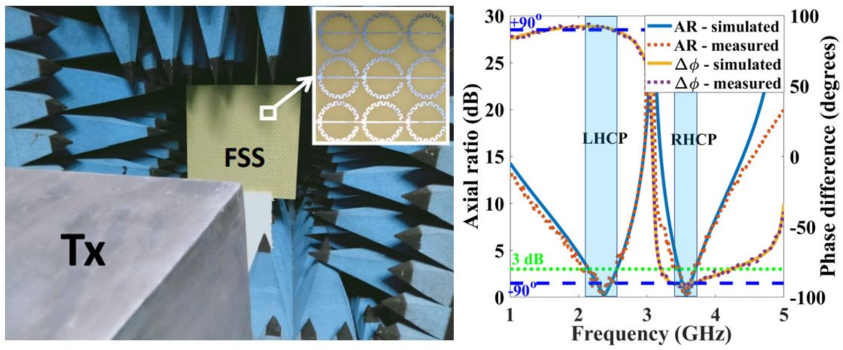


(a) (b)

Figure 4: (a)Fabricated prototype (b)Absorptive characteristics of proposed absorber.

4 Design of FSS Based Microwave Polarizer

The proposed polarizer is fabricated on a 297×297 mm^2 substrate and tested in an anechoic chamber as shown in Fig. 5(a). The calculated AR and phase difference of the measured versus simulated values are plotted in Fig. 5(b). The measured values show two CP bands in the frequency ranges 2.06 to 2.6 GHz and 3.37 to 3.77 GHz. The ARBW of the first band converted to LHCP is 23% and the second band converted to RHCP has an ARBW of 11%. The model has scan capability due to its highly compact cell structure but it is limited to ±30° due to its anisometric design. The compact dual-band FSS based polarizer has been designed with operating frequencies centered at 2.38 and 3.57 GHz. The proposed structure with meandered split rings are periodically intersected



(a) (b)

Figure 5: (a)Measurement setup (b)Frequency response.

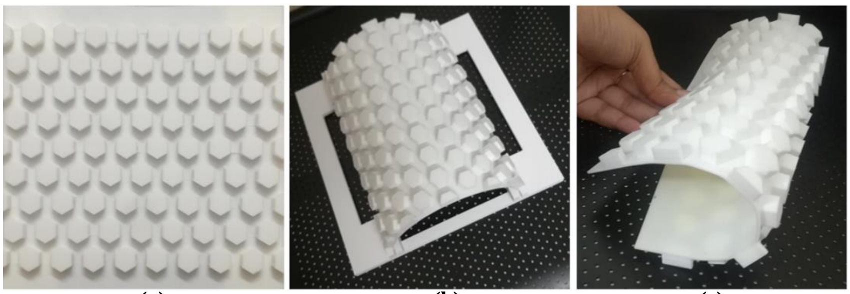
onto a cell-interconnected metal strip to deliver two closely spaced CP conversion bands. The bands are well isolated due to orthogonal sense polarization conversion. The single layered model provides design flexibility and ease in frequency scalability.

5 FSS with Additive Manufacturing

Apart from the angular and polarization stability, the FSS used in practical applications would also need to have conformal stability as they are required to fit in systems which have pre-determined shape. In this aspect 3D FSS elements have superior performance than their planar counterparts as they reduce angular sensitivity and promote improved field of view. However, such 3D structures could make the system heavy and bulky. Hence to build such structures with arbitrary shapes and controlled mass an innovative manufacturing technology like AM can be used.

5.1 All-dielectric FSS (ADFSS) reflector

The simulated model of a Ku-band ADFSS with hexagonal projections is additively manufactured using FDM printer into a 220×220 mm^2 model. The photograph of the proposed prototype is shown in Fig. 6(a). A PLA frame is also printed for steady placement of the model in the normal and conformal position with a radius of 7 cm during far-field measurement. The FSS ready for conformal test is shown in Fig. 6(b). The flexibility of the model can be visualized from Fig. 6(c). The simulated and measured values plotted in Fig. 7(a) shows good reflection in the operating frequency range of 14.7 to 15.4 GHz. The four-fold symmetry of the structure ensures polarization independence under TE and TM mode. The simulations are verified experimentally in Fig. 7(b).



(a) (b) (c)

Figure 6: Photograph of prototype (a) top view (b) isometric view (c) flexibility.

5.2 AM based FSS reflector and antenna

The dielectric layer for the proposed antenna and reflector models have been 3D printed with PLA using an FDM process. A conductive metal aerosol via a negative mask is used

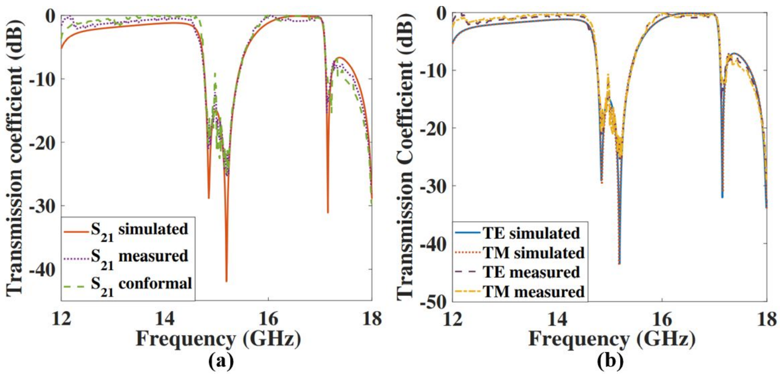


Figure 7: (a)ADFSS characteristics (b)ADFSS under TE & TM mode.

to form the loop array of the FSS and conductive parts of the antenna. The measurement setup for transmission coefficient under normal incidence as shown in Fig. 8(a) is used to validate a flat FSS prototype with a surface dimension of 285 × 250 mm^2. The conformal version of this prototype is measured with the same setup as shown in Fig. 8(b). The simulated and measured results of the FSS prototype are compared in Fig. 8(c). It shows that the fabricated FSS works as a reflector in the frequency ranges of 2.76 to 4.32 GHz and 2.94 to 4.25 GHz for flat and conformal type FSS, respectively. The presented FSS due to its symmetric and sub-wavelength nature has good angular stability and polarization independence. To further validate the AM based FSS prototype, a monopole antenna is designed for the same frequency band whose gain characteristics are improved using the FSS reflector. To retain the reflection characteristics of the antenna and FSS, the distance between them has been optimized to 17 mm. The FSS placed below can be used to enhance the gain of the proposed antenna. For the present case study an average gain improvement of 3.5 dBi in the antennas operating frequency range of 3.07 to 3.74 GHz was observed.

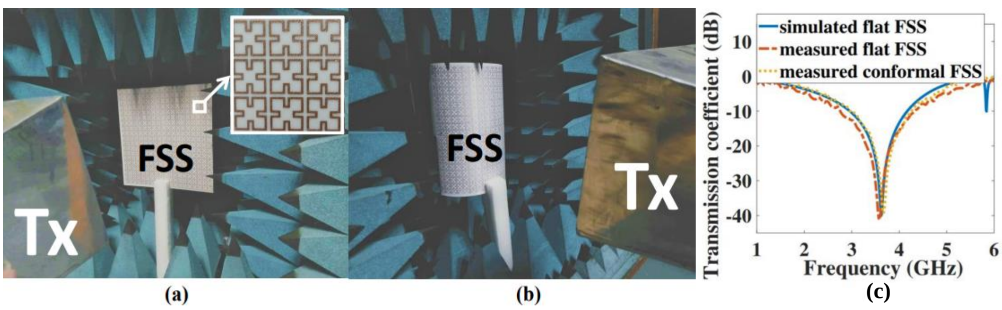


Figure 8: Measurement setup for S_{21}: (a) Flat FSS (b) Curved FSS (c) FSS characteristics.

From the measured results it can be inferred that the performance of the 3D printed microwave components is in no way inferior to its PCB manufactured counterparts. It can be summarized that by adopting AM for microwave component manufacturing, one can not only increase the design freedom but also achieve rapid prototyping with economic benefits. The components built with AM can also be made eco-friendly by utilising environment friendly raw materials

6 Conclusions and Future Work

6.1 Conclusions

The main objective of the thesis is to introduce various structural modeling techniques to develop miniaturized wideband and multi-band FSS components such as reflectors, absorbers and polarizers. Miniaturization in terms of cell size contributes to better performing FSS which have stable frequency response for oblique incidence, varied polarizations and conformal structures. Based on a critical survey of various state-of-art FSS components few novel single layered structural design techniques have been proposed to obtain compact and high performing FSS prototypes. ECM for all the proposed FSS aid the reader in validating the frequency behaviour of the FSS. The frequency response which is dominantly affected by the structural parameters of the FSS are emphasized using parametric analysis. The simulated and measured results of the proposed FSS are compared with existing works. The results show that the presented FSS have better characteristics in terms of compactness, angular stability, polarization independence, FBW and frequency ratio. The widely progressive technology of AM has also been adapted for FSS prototyping and its various advantages are portrayed by analysis of planar and 3D FSS reflector. Moreover, the current shortcomings in AM were also discussed which could soon be overcome with the steady advancement in emerging AM materials.

6.2 Suggestions for Future Work

While a large number of design scenarios exist for FSS cell miniaturization which effectively improves its performance, only the singe layered, vialess, planar FSS with absence of active/passive component have been considered in this thesis. However, rapid progress in AM technologies has opened new possibilities to develop miniaturized FSS with superior performance. The 3D or cascaded FSS which conventionally require complex manufacturing can now be built with ease using AM. With the advent of conductive printing filaments the possibility of building complex via based FSS with a single step process and minimal manufacturing error can be explored. Module manufacturing in AM eliminates the need for wired interconnects and component soldering in active element FSS by replacing them with printed interconnects. This can greatly improve component reliability of complex structural models.

7 Proposed Contents of the Thesis

The thesis is organized as follows:

1. Introduction
    1.1 Introduction to frequency selective surfaces
    1.2 Structural classification of FSS
    1.3 Functional classification of FSS
    1.4 Literature Review and objectives
    1.5 Contribution of this Thesis
    1.6 Thesis Organization
2. Design of Frequency Selective Surface Based Microwave Reflectors
    2.1 Introduction
    2.2 Design of dual-band miniaturized FSS based reflector
    2.3 Design of wide-band miniaturized FSS based reflector
    2.4 Design of multi-band miniaturized FSS based reflector
3. Design of Frequency Selective Surface Based Microwave Absorber
    3.1 Introduction
    3.2 Design of quad-band miniaturized FSS based absorber
4. Design of Frequency Selective Surface Based Microwave Polarization Convertor
    4.1 Introduction
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5. Frequency Selective Surface with Additive Manufacturing
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    5.2 Summary of AM technologies used in RF engineering
    5.3 AM Material Characterisation
    5.4 Design of single-band All-dielectric FSS based reflector
    5.5 FSS for Gain Enhancement of sub-6 GHz Antenna
6. Conclusions and Future Work
7. List of Publications

8 Publications

8.1 Papers in refereed journals

1. **R. Adeline Mellita**, Chandu DS and S. S. Karthikeyan, “A novel open loop design technique for frequency selective surface miniaturization,” *Microwave and Optical Technology Letters*, vol 60, no. 10, pp. 2599-2604, Oct. 2018.

2. **R. Adeline Mellita**, Chandu DS, S. S. Karthikeyan and P. Damodharan, “A miniaturized wideband frequency selective surface with interconnected cell structure,” *AEU - International Journal of Electronics and Communications*, Vol. 120, pp. 153-196, Jun. 2020.

3. **R. Adeline Mellita**, S. S. Karthikeyan, P. Damodharan and Chandu DS, “A miniaturized quad-band frequency selective surface for C-band applications,” *Journal of Electromagnetic Waves and Applications*, vol 35, no. 14, pp. 1882-1893, May 2021.

4. **R. Adeline Mellita**, S. S. Karthikeyan and P. Damodharan, “Ultrathin dual-band transmissive linear to circular polarizer for S-band applications,” *IEEE Microwave and Wireless Component Letters*. (Under review).

5. **R. Adeline Mellita**, S. S. Karthikeyan and P. Damodharan, “Additively manufactured frequency selective surface for gain enhancement of sub-6 GHz antenna,” *Journal of Electromagnetic Waves and Applications*. (Under review).

8.2 Presentations in international conferences

1. **R. Adeline Mellita**, S. S. Karthikeyan and P. Damodharan, “An ultrathin quad-band microwave absorber with small frequency ratio,” In Proc. 49^{th} *European Microwave Conference (EuMC 2019)*, Paris, France, pp. 674-677, Oct. 2019.

2. **R. Adeline Mellita**, S. S. Karthikeyan and P. Damodharan, “Additively manufactured conformal all-dielectric frequency selective surface,” In Proc. 50^{th} *European Microwave Conference (EuMC 2020)*, Utrecht, Netherlands, pp. 772-775, Jan. 2021.

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