Savunma Bilimleri Dergisi, 20(2): 211-222 (2024)

SAVUNMA BİLİMLERİ DERGİSİ
The Journal of Defense Sciences

https://dergipark.org.tr/tr/pub/khosbd

Conformal Frequency Selective Surfaces in Radome Design: A Mini Review

Radom Tasarımında Konformal Frekans Seçici Yüzeyler Üzerine Kısa bir Değerlendirme

Nagihan Aybegüm KORKUT [1,2,*] , Funda Ergün YARDIM[2] , Ali KARA[2]

1 Türk Havacılık ve Uzay Sanayii AŞ. Fethiye Mahallesi, Havacılık Bulvarı No:17 06980 Kahramankazan Ankara

2 Gazi University Graduate School Of Natural And Applıed Scıences Department of Electrical and Electronics Engineering 06500, Teknikokullar, Ankara

Makale Bilgisi

Derleme
Başvuru: 20.07.2024
Düzeltme: 03.09.2024
Kabul: 17.09.2024

Keywords

Conformal Frequency Selective Surfaces (FSS)
Radomes
Aerospace Engineering

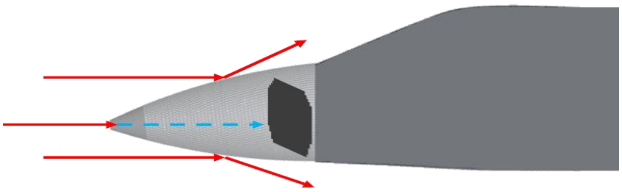
Anahtar Kelimeler

Konformal Frekans Seçici Yüzeyler (FSY)
Radom
Havacılık Mühendisliği

Highlights

Konformal frekans seçici yüzeyler (FSY) üzerine yapılan çeşitli araştırmaları inceleyen bu derleme, bu teknolojinin radar ve iletişim sistemlerinde sunduğu avantajları ve dezavantajları tartışmaktadır.Konformal FSY'lerin esnek yapısı sayesinde karmaşık yüzeylere uyum sağlaması ve elektromanyetik performansı optimize etmesi, çalışmaların ortak noktalarıdır. Kullanılan malzemeler, tasarım teknikleri ve uygulama alanları arasında farklılıklar belirtilmiştir.Makale, konformal FSY radomlarının elektromanyetik performanslarını artırma potansiyelini vurgular ve gelecekteki araştırmalar için yönlendirici öneriler sunar.

Graphical Abstract



Abstract

In aerospace engineering, radomes play an important role in protecting antenna systems from external interference and minimizing air resistance during flight. However, conventional radomes generally fail to offer the necessary electromagnetic filtering and stealth properties crucial for new generation aircrafts. Conformal Frequency Selective Surface (FSS) radomes are a significant advancement over traditional designs. In addition to shielding antenna structures from environmental challenges, these radomes conform smoothly to curved surfaces. This design is not only functional but also addresses aerodynamic and aesthetic concerns, enhancing stealth performance and multi-band frequency functionality, both crucial for advanced communication and radar systems. However, design and implementation of conformal FSS radomes have some challenges. Focusing on such challenges for new generation air platforms, this study examines the contemporary advancements in conformal FSS radome technology, highlighting the latest research and breakthroughs. It covers latest findings on cutting-edge materials, design methodologies, simulation techniques for performance prediction, and the practical applications and advantages of these radomes. Building on a theoretical foundation of FSS and radome integration, the article discusses material and design innovations, simulation challenges, and practical implementations. This review is expected to facilitate knowledge exchange and stimulate further research in the field of conformal FSS radome technology.

Özet

Havacılık mühendisliğinde, radomlar anten sistemlerini dış müdahalelerden koruma ve uçuş sırasında hava direncini en aza indirme konusunda önemli bir rol oynar. Ancak, geleneksel radomlar yeni nesil uçaklar için gerekli olan elektromanyetik filtreleme ve gizlilik yeteneklerini sağlama konusunda genellikle yetersiz kalır. Konformal Frekans Seçici Yüzey (FSS) radomlar, geleneksel tasarımlara göre önemli bir ilerlemedir. Anten yapılarını çevresel zorluklardan korumaya ek olarak, bu radome'lar kavisli yüzeylere de sorunsuz bir şekilde uyum sağlar. Bu tasarım sadece işlevsel olmakla kalmaz, aynı zamanda aerodinamik ve estetik endişeleri de dikkate alır, görünmezlik performansını ve çok bantlı frekans işlevselliğini artırarak, gelişmiş iletişim ve radar sistemleri için kritik öneme sahip özellikleri sağlar. Ancak, konformal FSY radomların tasarım ve gerçeklenmesinde bazı zorluklar bulunmaktadır. Yeni jenerasyon hava platofrmları için bu tip zorluklara odaklanılarak, bu çalışma, konformal FSY radom teknolojisindeki çağdaş gelişmeleri incelemekte, en son araştırmaları ve atılımları vurgulamaktadır. Son teknoloji malzemeler, tasarım metodolojileri, performans tahmini için simülasyon teknikleri ve bu radomların pratik uygulamaları ve avantajları hakkında son gelişmeleri ele alınmaktadır.Bu çalışma, FSY ve radom entegrasyonunun teorik temeli üzerine inşa edilerek, malzeme ve tasarım yeniliklerini, simülasyon zorluklarını ve pratik uygulamaları tartışmaktadır. Bu incelemenin, konformal FSS radom teknolojisi alanında bilgi alışverişini kolaylaştırması ve daha fazla araştırmayı teşvik etmesi beklenmektedir.

---

*Corresponding author, e-mail: naybegum.korkut@gazi.edu.tr

DOI: 10.17134/khosbd.1519500

Elektronik/Online ISSN:1303-6831
Basılı/Printed ISSN:2148-1776

1. INTRODUCTION

Conformal frequency-selective surfaces are used in many fields as structures that allow electromagnetic waves of specific frequencies to pass through or to be reflected. First, in radar systems they are used to reduce the radar cross-section area by allowing radar signals of specific frequencies to pass through, thus increasing the stealth of aircraft. Second, in telecommunications systems they can be used to filter unwanted frequencies and reduce signal noise. Third, these surfaces play an important role in satellite communication systems by optimizing the frequency band and minimizing interference.

In the complex world of aerospace engineering, radomes serve a dual purpose: they are crucial in protecting antenna systems from external effects including rain, hail and birds as well as interference, and play a pivotal role in minimizing air resistance during the flight [1-2]. Traditional radomes, however, often fall short in providing electromagnetic filtering and stealth capabilities—features that are increasingly essential for modern aircraft applications. The introduction of frequency selective surfaces (FSS) into radome technology has marked a significant leap forward. The ground-breaking research [3] been highly known in FSS radome design for modelling electromagnetic wave propagation, designing elements for selective filtering of frequencies, thus enabling radomes to protect antennas while still facilitating the transmission of desired signals.

Conformal FSS radomes represent an evolutionary step beyond their traditional counterparts. These structures not only maintain the essential function of protecting antenna system from environmental adversities but also adapt seamlessly to non-planar surfaces. This adaptation is not merely functional but encompasses aerodynamic and aesthetic considerations, enhancing the stealth capabilities and multi-band frequency operability—key factors for state-of-the-art communication and radar systems.

Frequency Selective Surfaces themselves are complex structures composed of periodically arranged patterns on substrates, acting as filters to control transmission, absorption and reflection of electromagnetic (EM) waves. Basically, FSS address selective blocking, reflecting, or transmission of some frequencies of EM waves – simply, a capability natural material does not possess [4]. When integrated into conventional radomes, FSS radomes achieve a substantial reduction in Radar Cross Section (RCS) for the enclosed antenna systems outside their operating frequency range [5]. These frequency selective surfaces, part of a broader category that includes metamaterials and plasmonic materials, harness engineered properties such as tunable permittivity and permeability, granting unprecedented control over EM wave behaviour [6]. Despite their promise, the implementation of conformal FSS radomes is very challenging. Designers must navigate a complex landscape, balancing material characteristics, geometric configurations, and electromagnetic behaviour over curved surfaces. The symbiosis of computational methods and material science has propelled the field forward, allowing for the development of innovative solutions that address these multifaceted challenges.

Considering that one of the authors has focused on such challenges for new generation air platforms, this review study attempts to highlights some unnoticed progresses in conformal FSS radome technology, examining the latest research and breakthroughs within this niche domain. It has studied the materials and design methodologies at the vanguard, assessed the simulation techniques critical for performance prediction and analysis, and contemplated the practical applications and operational advantages that these radomes offer. Structured to build upon a theoretical foundation of FSS and their integration into radomes, the article has progressed to discuss material and design innovations. Then it has analysed the simulation challenges and practical implementation, aiming to provide a thorough overview of current applications and future potential. It is hoped that this review will act as a bridge for knowledge sharing and a stimulant for continued research within the domain of conformal FSS radome technology.

2. REVIEW OF FREQUENCY SELECTIVE SURFACES (FSS)

2.1. Overview of Modelling and Design Principles of FSS

Frequency Selective Surfaces (FSS) functions as a spatial filter, which resembles traditional microwave filters within the context of circuit theory. The filtering capabilities of an FSS are diverse, encompassing four primary types: low-pass, high-pass, band-stop, and band-pass. For example, a low-pass FSS configuration is utilized to allow frequencies below a certain cutoff to transmit through its structure, effectively attenuating frequencies above this threshold. A high-pass FSS achieves the opposite effect. Then, the band-stop variant of an FSS rejects a specific range of undesired frequencies, whereas the band-pass variant selectively transmits a designated frequency range [4].

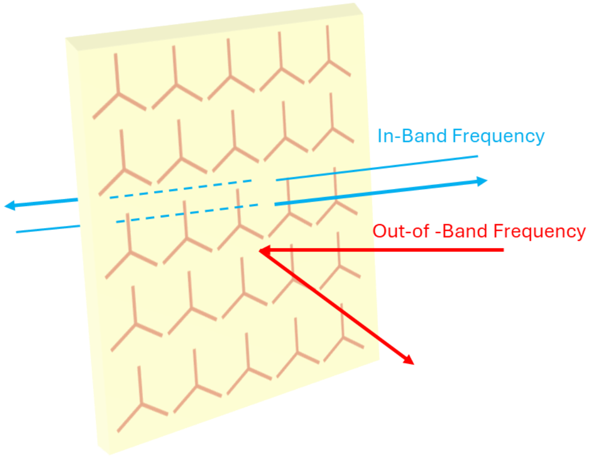


Figure 1: Illustration of the Functionality of a Frequency Selective Surface (FSS).

The design of FSS involves arrangement of conductive elements into a periodic pattern, typically involving metallic patches or apertures on a dielectric base. The first critical step is the selection of the elements, that is, shape, size, and the properties of the substrate, to ensure the FSS meets the desired resonant criteria. The following formula is well-known for expressing resonant frequency of an FSS encompassing capacitive (C), inductive (L) and resistive (R) effects within and in between the elements

$$f_r = \frac{1}{2\pi\sqrt{LC}} \qquad (1)$$

By employing fundamental concepts of electromagnetics, these passive component values can be adjusted to tailor the FSS's frequency response. Then, it seems to be strategic play around these inductive and capacitive elements that a specific filter response is crafted. Dimensioning of the FSS also corresponds to variations of the values of L and C. When an electromagnetic (EM) wave interacts with an FSS's unit cell, the cell behaves as if it were a resonance circuit with equivalent properties. Selecting the appropriate element of the array is critical in the design of FSS. While various unit cell configurations have been employed, some of which are easily controllable and thus more popular in the FSS community.

For surfaces selectively focusing on frequency (FSS), the shape of the unit cells is dependent on their resonance properties and can be categorized geometrically as square, circular, or fractal. Each type of geometry has a different response to incident electromagnetic wave, this affects the behaviour of the FSS in resonance. For instance, square cells often have a specific frequency of resonance that is determined by their dimensions, while circular cells have a broader range of response characteristics. On the other hand, fractal unit cells, with their complex patterns that are self-similar, have a unique response that can be altered for specific purposes. By choosing the appropriate cell geometry and periodic arrangements within the FSS, designers can create surfaces that have specific transmission and reflection properties for targeted applications.

In the FSS unit cell, capacitance (C) and inductance (L) are the basic parameters that determine the frequency response of electromagnetic waves. Capacitance generally represents the storage capacity of the electric field within the unit cell, while inductance refers to the storage capacity of the magnetic field. These two parameters directly affect the resonant frequency of the unit cell and affect the overall performance of the system. By accurately determining and optimizing L and C, the FSY structure can work effectively within the required frequency range. For example, the circuit structure of the low-pass filter and high-pass filter is shown in Figure 2.

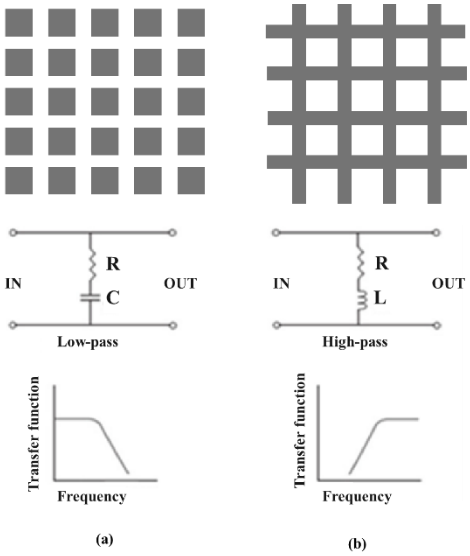


Figure 2: Periodic Structures Composed of Complementary Elements Can Be Designed As (A) Low-Pass And (B) High-Pass Filters, Each With Their Respective Equivalent Circuits and Frequency Responses (Metallic-Grey Colour). In These Designs, The Patch Array Exhibits A Capacitive Response, Whereas The Slot Array Demonstrates An Inductive Response [4].

The impedance qualities of periodic structures can be evaluated through two techniques: the mutual impedance (or element-to-element) method and the plane wave expansion (or spectral) method. For designing periodic FSS-based electromagnetic structures, Floquet's theorem can be utilized. This theorem indicates that the solution will exhibit identical periodicity [4]. Let a planar array extends infinity in the x- and z-directions, featuring uniform inter-element spacing ($D_x = D_z$) is termed as a truly periodic configuration (infinite × infinite) and is shown in Figure 3.

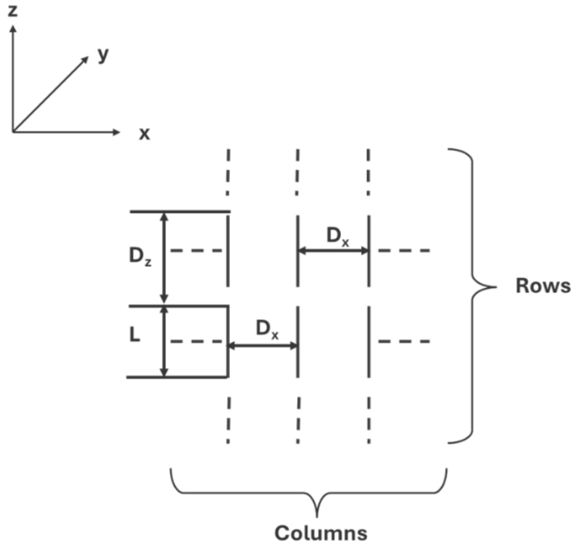


Figure 3:A True Periodic Structure Showing Inter-Element Spacing (D_x And D_z) and Element Length of L.

This is a truly periodic configuration and is infinitely extended on the xz plane. Let an incident electromagnetic wave traveling in a specific direction strikes on this array [7]. The currents across an entire element of FSS, induced due to the incident wave, exhibits equal amplitudes, with the phase of the incident electromagnetic (EM) field aligning with the phase of the induced current. The periodicity in the array leads to periodic variations in the induced current and voltage along the configuration. Floquet's theorem helps to determine the fundamental harmonic of these periodic variations. According to Floquet's theorem, the currents associated with column *m* and row *n* of the element can be written as follows [8]:

$$I_{mn} = I_{0,0} e^{-j\beta m D_x s_x} e^{-j\beta n D_z s_z} \tag{2}$$

Where $I_{0,0}$ is the amplitude of current at the centre (0,0), β is the phase constant, $s_{x,y}$ is the unit vector in x and y axis. Employing Ohm's law with respect to the reference element at the centre results in the following equations.

$$V^{0,0} = \left[Z_L + \sum_{m=-\infty}^{\infty} \sum_{n=-\infty}^{\infty} Z_{0,mn} e^{-j\beta m D_x s_x} e^{-j\beta n D_z s_z}\right] I_{0,0} \tag{3}$$

$$Z^{0,0} = \sum_{m=-\infty}^{\infty} \sum_{n=-\infty}^{\infty} Z_{0,mn} e^{-j\beta m D_x s_x} e^{-j\beta n D_z s_z} \tag{4}$$

It should be noted that the repetitive nature of unit cells in FSS leads to periodic variations in the voltage and current as well as impedances. To maintain a focused scope on recent research and findings, we prefer not to dive into the full formulation and modelling aspects of FSS arrays.

Conformal frequency selective surfaces have several benefits compared with planar frequency selective surfaces. They are adaptable for applications where integration of the FSS with non-planar surfaces are required. They also allow better control of electromagnetic waves, the reflection and the transmission properties. These conformal radomes are ideal for applications where aesthetics is crucial, as they can seamlessly blend in with complex shapes.

Conformal FSS adapt to curved radome structures with ease, reducing aerodynamic disturbances and enhancing overall efficiency. This characteristic is very critical for improving the aircraft stealth while reducing the radar cross-section. Moreover, because of conformal nature, they are more effectively integrated with the aerodynamic profile of the aircraft, guaranteeing optimal airflow and decreased platform drag. These benefits show conformal frequency selective surfaces' superiority for radome applications in airborne platforms and emphasize their crucial role in the functionality and design of high-speed, high manoeuvrability aircrafts.

Conformal frequency selective surfaces (FSS) provide numerous benefits, but there are also drawbacks and difficulties to consider while designing them. Since the curvature of the surface might change the frequency response, one major problem is how difficult it is to achieve the necessary electromagnetic performance when the surface is curved. To precisely forecast and optimize the behaviour, complex computational models and simulations are needed. Furthermore, because the FSS must be conformed to non-planar surfaces, precise manufacturing procedures are required, increasing the complexity and cost of the production process. Another problem is choosing the right material because it must have the necessary electromagnetic properties and be flexible enough to bend without compromising its structural integrity. These elements may result in longer and more expensive design and production cycles, necessitating meticulous planning and cutting-edge technology [20, 21, 25].

2.2. Review of State-of-Art in Conformal Frequency Selective Surfaces

This section attempts to highlights some unnoticed research in conformal FSS radome technology, reviewing the latest research and breakthroughs within this niche domain. Conformal FSS have been extensively researched. The studies mainly focus on the performance of unit cell design of FSS for a particular band. An innovative fractal frequency selective surface (FSS) is proposed [9] for dual-bandpass applications in the C and X frequency bands. The structure is centrally symmetric and uses the golden ratio fractal geometry for dual band characteristics. The results confirm potential of the designed FSS for applications requiring low visibility and dual bandpass performance. The design and performance analysis of a low-junction loss, polarisation insensitive, FSS-antenna-radome system is proposed [10] within the X-band operation (9.6-10.7 GHz). The simulations show that the system achieves a -10 dB reflection over the entire X-band with high gain as well as significantly low insertion loss, ranging from 0.04 to 0.15 dB. An interesting study [11] presents design and analysis of a triangular conical band-pass FSS radome which selectively passes certain frequency band. On step further [12], an integrated freestanding thick-screen FSS radome, but for enhancing the stealth capability of flying weapons, selectively passes certain frequency bands while blocking the remaining. The FSS radome has Y-shaped apertures and is manufactured using a spin-forming process for the copper shell and followed by fine-tuning with precision laser robot system. This achieves approximately 80% pass-band transmissivity while less than 10% stop-band transmissivity. The system is tested in an anechoic chamber and demonstrated experimentally. A novel-shaped jigsaw band-pass FSS (JS-FSS), inspired by ancient Chinese hinge and wedge joints, is proposed [13]. The motivation seems to be mechanical flexibility and avoid cracking in printed lines when bent. The proposed JS-FSS shows an improved angular stability by maintaining band-pass performance for TE and TM polarizations at various incident angles. It is experimentally shown that the band-pass performance of the JS-FSS changes with the curvature radii, indicating that smaller radii increase the mutual coupling between elements, thereby affecting the frequency response. A filter-antenna system combining a monopole operating at around 6.1 GHz with a conical FSS radome is proposed [14] for military applications where low RCS and electronic countermeasures are targeted. The FSS radome employs a coupled-resonator spatial filter (CRSF), which offers high selectivity, low insertion loss, and stable performance for different incident angles and polarizations. This makes CRSF a very good candidate for hybrid FSS radome applications.

Flexibility and reconfigurability is another attractive research domain. A flexible and frequency reconfigurable band-stop frequency selective surface (FSS) is experimentally demonstrated [15]. The FSS is fabricated on an ultra-thin flexible substrate using the additive manufacturing method of screen printing. Having a unit cell of λ/15 size at 3.5 GHz, the FSS achieves high performance when conformally mounted on a semi-cylinder of 10 cm diameter, demonstrating its potential for flexible and conformal applications. Another flexible and low-profile FSS for X-band operation is reported [16] for reducing electromagnetic interference (EMI) in dense communication environments. It utilizes convoluted ring loop (CRL) elements on a specially coated Polyethylene Terephthalate (PET) substrate. The FSS prototype is produced using an inkjet printing technique with silver nanoparticle ink, which becomes conductive through a chemical sintering process, resulting in a fast and efficient production compared to traditional thermal sintering. A microwave polarizer designed using frequency selective surfaces (FSS) loaded with complementary split ring resonators (CSRRs) [17] is fabricated on a flexible 50μm thick liquid crystal polymer (LCP) base for non-planar and conformal FSS applications. The polarizer exhibits minimal transmission loss for TE-polarization input waves (0.75dB at 10.24GHz) and a higher loss for TM-polarization input waves (19.05dB). This provides a polarization extinction ratio of 18.3dB, demonstrating effective polarization selectivity for FSS applications. For low frequency civil applications, a miniaturized dual-band FSS [18] is designed for curved surface applications, targeting wireless local area network (WLAN) frequencies (2.4 GHz and 5.5 GHz) where the FSS is mounted on a single metal layer printed circuit board (PCB). This FSS is flexible, allowing for the adjustment of element sizes by changing the substrate thickness to create either compact designs for different applications or very thin substrates. Additionally [27, 29, 30] and [32] have realised the design of a flexible conformal frequency selective surface in X band for the EM Shielding application area.

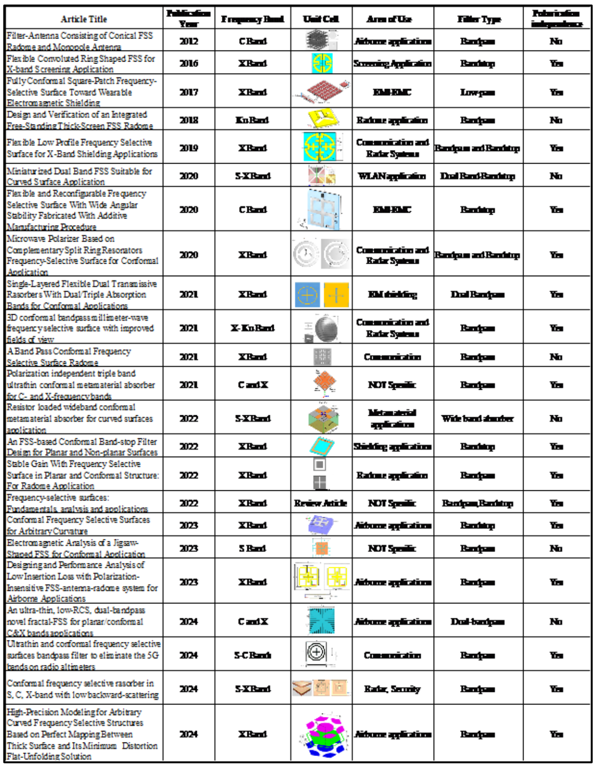
The design and analysis of FSS for radome applications on air platforms, focusing on maintaining stable antenna gain in both flat and conformal structures is presented [19]. Simple square slot and cross dipole slot elements made of low-cost FR-4 is utilized to overcome the complexity of FSS design for conformal air platforms. This FSS is attractive for minimization of FSS impact on the antenna system.

In contrast to conventional manufacturing methods, 3D printing was used in [22], and the structure was coated with copper through electrolysis, resulting in a more cost-effective and lightweight design. It has been demonstrated that the produced conformal frequency selective surface can be used as a radome by placing it in the near-field region of the antenna to realize compact high-performance mm-wave systems.

With advancing technology, different design methods have also found their place in the literature. Especially with the algorithms developed for conformal surfaces, designs independent of surface curvature have been developed. In [26], an algorithm was developed to produce frequency selective surfaces (FSS) that can adapt to any curvature while preserving the size, shape, and spacing of the unit cells that form the frequency selective surface. This algorithm is independent of both element design and surface curvature, enabling it to create applicable designs for radomes, autonomous vehicles, and surfaces with any curvature. This also made the algorithm suitable for 3D printing using systems with more than three axes or for flexible electronics. In [28], based on the elastic deformation theory of thin shells, a perfect mapping was created between a curved surface and a planar array using the weighted minimum distortion flat unfolding solution of the surface, which was then extended to 3D (Three-Dimensional) conditions along the thickness direction. This paper presents a class of local unit-cell deformation control algorithms. The application impact and potential of this method are demonstrated with an example of an augmented conical radome using a three-layered hybrid unit cell.

The list of articles reviewed in this study can be found in Table 1.

Table 1: The List of Articles Reviewed In This Study [2-32].



Article Title	Publication Year	Frequency Band	Unit Cell	Area of Use	Filter Type	Polarization independence
Filter-Antenna Consisting of Conical FSS Radome and Monopole Antenna	2012	C Band		Airborne applications	Bandpass	No
Flexible Convoluted Ring Shaped FSS for X-band Screening Application	2016	X Band		Screening Application	Bandstop	Yes
Fully Conformal Square-Patch Frequency-Selective Surface Toward Wearable Electromagnetic Shielding	2017	X Band		EMI-EMC	Low-pass	Yes
Design and Verification of an Integrated Free-Standing Thick-Screen FSS Radome	2018	Ku Band		Radome application	Bandpass	No
Flexible Low Profile Frequency Selective Surface for X-Band Shielding Applications	2019	X Band		Communication and Radar Systems	Bandpass and Bandstop	Yes
Miniaturized Dual Band FSS Suitable for Curved Surface Application	2020	S-X Band		WLAN application	Dual Band-Bandstop	No
Flexible and Reconfigurable Frequency Selective Surface With Wide Angular Stability Fabricated With Additive Manufacturing Procedure	2020	C Band		EMI-EMC	Bandstop	Yes
Microwave Polarizer Based on Complementary Split Ring Resonators Frequency-Selective Surface for Conformal Application	2020	X Band		Communication and Radar Systems	Bandpass and Bandstop	Yes
Single-Layered Flexible Dual Transmissive Rasorbers With Dual/Triple Absorption Bands for Conformal Applications	2021	X Band		EM shielding	Dual Bandpass	Yes
3D conformal bandpass millimeter-wave frequency selective surface with improved fields of view	2021	X- Ku Band		Communication and Radar Systems	Bandpass	Yes
A Band Pass Conformal Frequency Selective Surface Radome	2021	X Band		Communication	Bandpass	No
Polarization independent triple band ultrathin conformal metamaterial absorber for C- and X-frequency bands	2021	C and X		NOT Specific	Bandpass	Yes
Resistor loaded wideband conformal metamaterial absorber for curved surfaces application	2022	S-X Band		Metamaterial applications	Wide band absorber	No
An FSS-based Conformal Band-stop Filter Design for Planar and Non-planar Surfaces	2022	X Band		Shielding applications	Bandstop	Yes
Stable Gain With Frequency Selective Surface in Planar and Conformal Structure: For Radome Application	2022	X Band		Radome application	Bandpass	Yes
Frequency-selective surfaces: Fundamentals, analysis and applications	2022	X Band	Review Article	NOT Specific	Bandpass,Bandstop	Yes
Conformal Frequency Selective Surfaces for Arbitrary Curvature	2023	X Band		Airborne applications	Bandstop	Yes
Electromagnetic Analysis of a Jigsaw-Shaped FSS for Conformal Application	2023	S Band		NOT Specific	Bandpass	No
Designing and Performance Analysis of Low Insertion Loss with Polarization-Insensitive FSS-antenna-radome system for Airborne Applications	2023	X Band		Airborne applications	Bandpass	Yes
An ultra-thin, low-RCS, dual-bandpass novel fractal-FSS for planar/conformal C&X bands applications	2024	C and X		Airborne applications	Dual-bandpass	No
Ultrathin and conformal frequency selective surfaces bandpass filter to eliminate the 5G bands on radio altimeters	2024	S-C Band		Communication	Bandpass	Yes
Conformal frequency selective rasorber in S, C, X-band with low backward-scattering	2024	S-X Band		Radar, Security	Bandpass	Yes
High-Precision Modeling for Arbitrary Curved Frequency Selective Structures Based on Perfect Mapping Between Thick Surface and Its Minimum Distortion Flat-Unfolding Solution	2024	X Band		Airborne applications	Bandpass	Yes

3. CHALLENGES AND FUTURE DIRECTIONS

Designing conformal frequency selective surfaces (FSS) presents several challenges, primarily due to the inherent complexities introduced by their non-planar structures. The following are some major challenges and the causes of them:

- Element Size and Spacing: To provide constant performance at various frequencies, dual and multiband architectures must maintain element size. However, the curvature of these structures can alter the distance between pieces when they are modified to conformal geometries, which can impact the overall performance and resonant frequency.
- Resonant Frequency Shift: Shifts in resonant frequency can result from variations in the

spacing between components on a curved surface. For the intended filtering properties to be maintained throughout the surface, this calls for meticulous design modifications.

- Surface Curvature: One of the main challenges in designing FSS is fitting arbitrary curves without warping the pieces. Performance loss brought on by distorted elements can impair the surface's capacity to filter frequencies selectively.
- Complexity of Manufacturing: Complex manufacturing processes are sometimes required to create FSS on curved surfaces. Ensuring that the dielectric substrates and metallic layers are of superior quality and suit the specified shape without sacrificing functionality is a technically challenging task. The proper frequency responses, for instance, can be electromagnetically produced by 2.5 and 3D frequency selective surfaces; however, their integration and manufacturing processes do not necessarily align with those of radomes.
- Design Flexibility: Adding another level of complexity, it is necessary to achieve the necessary design flexibility to adapt FSS for different applications, such as antennas and electromagnetic shielding, while preserving performance.
- Polarisation Sensitivity: Because of their geometries, conformal FSS may react differently to various polarisation states, requiring designs that can account for or lessen polarisation effects.

To overcome these obstacles, sophisticated design algorithms, accurate manufacturing methods, and extensive testing are needed to make sure that performance is maintained while modifying FSS for conformal surfaces. For this reason, the following topics ought to be the main emphasis of upcoming research:

- Integration loss must be studied carefully while initial stage of the FSS design. FSS-antenna-radome system is expected to achieve high gain and low insertion loss, minimizing signal degradation.
- Further exploration of multi-band and wideband FSS designs are needed.
- Development of low-profile, lightweight and robust materials for conformal FSS applications are needed.
- Integration of FSS with the antenna system and providing stable gain over the operational band needs to be studied further.
- Scalability and manufacturability as well as maintenance of FSS radome need to be studied from operational point of view.
- Polarization aspects of FSS should be addressed in air platforms where various threats may have reconfigurability in polarization. This makes the FSS radome design more complicated.
- Majority of air platforms has low size-weight and power as well as cooling (SWaP-C) requirements. Then, miniaturization may play key role when thin and low profile FSS is needed to satisfy SWaP requirements.

4. CONCLUSION

This overview covers all aspects of the topic of conformal frequency selective surfaces from the more intricate and specialised area of conformal applications to the fundamental concepts of frequency selective surfaces. The theoretical foundation provided in the first parts lays the platform for a deeper grasp of the workings of FSS and prepares the reader for exploring the subtleties of conformal designs. The analysis techniques covered are essential resources that help engineers and academics forecast and maximise the performance of conformal frequency selective surfaces. We have emphasised important developments and breakthroughs in conformal frequency selective surfaces through a review of the literature, demonstrating a broad range of applications across many industries, such as defence, aerospace, and telecommunications.

This review also emphasises the inherent difficulties in developing conformal surfaces, despite the encouraging improvements. These difficulties result from the requirement to adhere to non-planar surfaces while preserving performance and functionality, which frequently introduces intricate electromagnetic interactions. Determining the appropriate frequency responses, maintaining manufacturing accuracy, and dealing with material limitations continue to be major obstacles. Looking ahead, these challenges may be overcome with continued advancements in material sciences and computational methodologies. To improve the performance and practical usability of conformal frequency selective surfaces, future research initiatives might concentrate on producing more advanced modelling tools, investigating new materials with flexible electromagnetic properties, and devising creative production methods.

All things considered, the field of conformal frequency selective surfaces is dynamic and has great promise for research and real-world applications. In order to achieve this fascinating field of study, it would be crucial to maintain multidisciplinary efforts in tackling present issues and seizing fresh chances.

ACKNOWLEDGMENTS

This research received no external funding.

AUTHORSHIP CONTRIBUTION STATEMENT

Nagihan Aybegüm KORKUT: Conceptual design, Research, Methodology, Writing - Draft, Visualising.

Funda Ergün YARDIM: Research, Writing

Ali KARA: Methodology, Reviewing and Editing

CONFLICTS OF INTEREST

The authors declare that they have no conflict of interest.

REFERENCES

[1] D. J. Kozakoff, Analysis of radome-enclosed antennas, 2nd ed., Norwood, MA: Artech House, 2010, pp. 3-4.

[2] B. Gao, S. Huang, Z. Ren, Y. Chen and X. Wang, "Design and Verification of an Integrated Free-Standing Thick-Screen FSS Radome," in IEEE Antennas and Wireless Propagation Letters, vol. 17, no. 9, pp. 1630-1634, Sept. 2018, doi: 10.1109/LAWP.2018.2859232.

[3] M. Okramcha and M. R. Tripathy, "Designing and Performance Analysis of Low Insertion Loss with Polarization-Insensitive FSS-antenna-radome system for Airborne Applications," 2023 10th International Conference on Signal Processing and Integrated Networks (SPIN), Noida, India, 2023, pp. 323-328, doi: 10.1109/SPIN57001.2023.10117350.

[4] B. Munk, Frequency selective surfaces: theory and design. New York, NY, USA: Wiley, 2000, pp. 3-4.

[5] Q. Chen, and Y. Fu, "A planar stealthy antenna radome using absorptive frequency selective surface, " Microw. Opt. Techn. Let., vol.56, no.8, pp. 1788-1792, 2014. https://doi.org/10.1002/mop.28442.

[6] M. Okramcha and M. R. Tripathy, "Designing and Performance Analysis of Low Insertion Loss with Polarization-Insensitive FSS-antenna-radome system for Airborne Applications," 2023 10th International Conference on Signal Processing and Integrated Networks (SPIN), Noida, India, 2023, pp. 323-328, doi: 10.1109/SPIN57001.2023.10117350.

[7] Anwar, Rana Sadaf, Lingfeng Mao, and Huansheng Ning. 2018. "Frequency Selective Surfaces: A Review" Applied Sciences 8, no. 9: 1689. https://doi.org/10.3390/app8091689.

[8] Yang, F.; Rahmat-Samii, Y. Electromagnetic Band Gap Structures in Antenna Engineering; Cambridge University Press: Cambridge, UK, 2009.

[9] Yogesh Solunke, Ashwin Kothari, " An ultra-thin, low-RCS, dual-bandpass novel fractal-FSS for planar/conformal C&X bands applications", AEU - International Journal of Electronics and Communications, Volume 175,2024,155073, ISSN 1434-8411, https://doi.org/10.1016/j.aeue.2023.155073.

[10] M. Okramcha and M. R. Tripathy, "Designing and Performance Analysis of Low Insertion Loss with Polarization-Insensitive FSS-antenna-radome system for Airborne Applications," 2023 10th International Conference on Signal Processing and Integrated Networks (SPIN), Noida, India, 2023, pp. 323-328, doi: 10.1109/SPIN57001.2023.10117350.

[11] Y. Xu, S. Zhang, S. Chen, and H. Zhao, "A Band Pass Conformal Frequency Selective Surface Radome," 2021 IEEE 6th International Conference on Signal and Image Processing (ICSIP), Nanjing, China, 2021, pp. 876-880, doi: 10.1109/ICSIP52628.2021.9688798.

[12] B. Gao, S. Huang, Z. Ren, Y. Chen, and X. Wang, "Design and Verification of an Integrated Free-Standing Thick-Screen FSS Radome," in IEEE Antennas and Wireless Propagation Letters, vol. 17, no. 9, pp. 1630-1634, Sept. 2018, doi: 10.1109/LAWP.2018.2859232.

[13] Y. Zhang, T. Dong, D. Sun, Y. Wang, and S. Lü, "Electromagnetic Analysis of a Jigsaw-Shaped FSS for Conformal Application," 2020 50th European Microwave Conference (EuMC), Utrecht, Netherlands, 2021, pp. 768-771, doi: 10.23919/EuMC48046.2021.9338094.

[14] H. Zhou et al., "Filter-Antenna Consisting of Conical FSS Radome and Monopole Antenna," in IEEE Transactions on Antennas and Propagation, vol. 60, no. 6, pp. 3040-3045, June 2012, doi: 10.1109/TAP.2012.2194648.

[15] T. Tian et al., "Flexible and Reconfigurable Frequency Selective Surface with Wide Angular Stability Fabricated With Additive Manufacturing Procedure," in IEEE Antennas and Wireless Propagation Letters, vol. 19, no. 12, pp. 2428-2432, Dec. 2020, doi: 10.1109/LAWP.2020.3034944.

[16] W. Y. Yong et al., "Flexible Convoluted Ring Shaped FSS for X-Band Screening Application," in IEEE Access, vol. 6, pp. 11657-11665, 2018, doi: 10.1109/ACCESS.2018.2804091.

[17] W. Li, Y. Lan, H. Wang, and Y. Xu, "Microwave Polarizer Based on Complementary Split Ring Resonators Frequency-Selective Surface for Conformal Application," in IEEE Access, vol. 9, pp. 111383-111389, 2021, doi: 10.1109/ACCESS.2021.3102942.

[18] P. -S. Wei, C. -N. Chiu, C. -C. Chou and T. -L. Wu, "Miniaturized Dual-Band FSS Suitable for Curved Surface Application," in IEEE Antennas and Wireless Propagation Letters, vol. 19, no. 12, pp. 2265-2269, Dec. 2020, doi: 10.1109/LAWP.2020.3029820.

[19] S. Dhegaya and L. Tanwar, "Stable Gain with Frequency Selective Surface in Planar and Conformal Structure: For Radome Application," 2022 Trends in Electrical, Electronics, Computer Engineering Conference (TEECCON), Bengaluru, India, 2022, pp. 97-102, doi: 10.1109/TEECCON54414.2022.9854836.

[20] X. Sheng, H. Wang, N. Liu and K. Wang, "A Conformal Miniaturized Bandpass Frequency-Selective Surface with Stable Frequency Response for Radome Applications," in IEEE Transactions on Antennas and Propagation, vol. 72, no. 3, pp. 2423-2433, March 2024, doi: 10.1109/TAP.2024.334967.

[21] Ankush Kapoor, Ranjan Mishra, Pradeep Kumar, Frequency selective surfaces as spatial filters: Fundamentals, analysis and applications, Alexandria Engineering Journal, Volume 61, Issue 6, 2022, Pages 4263-4293, ISSN 1110-0168, https://doi.org/10.1016/j.aej.2021.09.046.

[22] Fernández Álvarez, Humberto & Cadman, Darren & Goulas, Athanasios & Gómez, M. &

Engstrom, Daniel & Vardaxoglou, John Yiannis & Zhang, Shiyu. (2021). 3D conformal bandpass millimeter-wave frequency selective surface with improved fields of view. Scientific Reports. 11. 10.1038/s41598-021-91218-y.

[24] A. Gouda, R. K. Mishra and S. Ghosh, "An FSS-based Conformal Band-stop Filter Design for Planar and Non-planar Surfaces," 2022 IEEE Microwaves, Antennas, and Propagation Conference (MAPCON), Bangalore, India, 2022, pp. 506-510, doi:10.1109/MAPCON56011.2022.10047603.

[25] Anwar, R.S.; Mao, L.; Ning, H. Frequency Selective Surfaces: A Review. Appl. Sci. 2018, 8, 1689. https://doi.org/10.3390/app8091689.

[26] C. L. Valle, G. T. Carranza and R. C. Rumpf, "Conformal Frequency Selective Surfaces for Arbitrary Curvature," in IEEE Transactions on Antennas and Propagation, vol. 71, no. 1, pp. 612-620, Jan. 2023, doi: 10.1109/TAP.2022.3216960.

[27] P. Gurrala, S. Oren, P. Liu, J. Song and L. Dong, "Fully Conformal Square-Patch Frequency-Selective Surface Toward Wearable Electromagnetic Shielding," in IEEE Antennas and Wireless Propagation Letters, vol. 16, pp. 2602-2605, 2017, doi: 10.1109/LAWP.2017.2735196.

[28] H. Minjie, "High-Precision Modeling for Arbitrary Curved Frequency Selective Structures Based on Perfect Mapping Between Thick Surface and Its Minimum Distortion Flat-Unfolding Solution," in IEEE Access, vol. 12, pp. 30533-30543, 2024, doi: 10.1109/ACCESS.2024.3365541.

[29] Y. Fu, F. Ding, J. Jin, H. Cheng, Y. Yang, X. Zhou, Y. Dai, and H. Yang, "Conformal frequency selective rasorber in S, C, X-band with low backward scattering," Opt. Express 32, 16879-16890 (2024).

[30] M. M. Zargar, A. Rajput, K. Saurav and S. K. Koul, "Single-Layered Flexible Dual Transmissive Rasorbers with Dual/Triple Absorption Bands for Conformal Applications," in IEEE Access, vol. 9, pp. 150426-150442, 2021, doi: 10.1109/ACCESS.2021.3126197.

[31] Thulasiraman, Jayanandan & Alex, Zachariah. (2024). Ultrathin and conformal frequency selective surfaces bandpass filter to eliminate the 5G bands on radio altimeters. Microwave and Optical Technology Letters. 66. 10.1002/mop.34001.

[32] W. Y. Yong, T. Hartman and A. A. Glazunov, "Flexible Low Profile Frequency Selective Surface for X-Band Shielding Applications," 2019 Joint International Symposium on Electromagnetic Compatibility, Sapporo and Asia-Pacific International Symposium on Electromagnetic Compatibility (EMC Sapporo/APEMC), Sapporo, Japan, 2019, pp. 435-438, doi: 10.23919/EMCTokyo.2019.8893795.