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Overview of Frequency Selective Surface (FSS) Filters: Advancements in Fabrication Materials and Techniques

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ABSTRACT

This paper provides a general overview of fabrication materials and techniques for frequency selective structures (FSS) filter, from conventional printed circuit board (PCB)-based designs to ink, textile and metamaterial. Various fabrication techniques and solutions documented in numerous journal and conference publications are presented, and several examples of each approach are given. Theoretical aspects of FSS are explained to provide a basic understanding of the principles of the filter. In addition, key physical parameters with significant effects on FSS performance are identified, including the electrical conductivity of the conducting FSS element and the relative dielectric constant, as well as equivalent circuit models. The article concludes with a comparative analysis of the materials and techniques, highlighting the advantages and limitations of each method, while also addressing future challenges associated with their implementation.

Keywords:
Frequency Selective Surface (FSS) filter; fabrication method; FSS textile; printed circuit board; electromagnetic waves

1. Introduction

Frequency Selective Surface (FSS) filters are comprised of periodic arrangements of unit cells composed of slender quasi-two-dimensional (2D) surfaces or three-dimensional (3D) component [1]. These configurations exhibit distinctive frequency selectivity, enabling them to either reflect, transmit, or absorb electromagnetic waves [2,3]. In the realm of electromagnetics, FSSs are classified as spatial filters, given their ability to manipulate waves across various frequencies in open space. The advancement of contemporary wireless networks has underscored the necessity for innovative spatial frameworks rooted in FSSs to fulfill electromagnetic requisites. Nevertheless, conventional FSSs encounter limitations in their applicability due to their restricted bandwidth and diminished filtering efficacy, thus failing to satisfy the performance standards for electromagnetic purposes. Consequently, FSS exploration has emerged as a paramount area of investigation within electromagnetics, characterized by periodic formations. These formations typically feature flat

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metallic array components (such as patches or apertures) integrated onto a dielectric substrate, functioning as spatial filters within designated frequency range [3].

Selecting the physical mechanism that enables reconfigurability in metamaterial-enhanced devices is crucial in the design process, as it directly affects the achievable performance, cost, fabrication complexity, scalability, and flexibility of the resulting architecture. Maintaining optimal signal-to-noise (SNR) and signal-to-interference-plus-noise ratios (SINR) holds utmost importance for numerous transceivers. Within the terahertz (THz) spectrum, integrating an FSS filter instead of a traditional circuit filter can notably elevate both SNR and SINR levels. The advantages of having FSS filters compared to conventional circuit filters are cost-effective, feature diminished electrical losses and miniaturized [4,5]. The utilization of FSS technology spans various applications, including electromagnetic absorption, control of radar cross-section (RCS), mitigation of electromagnetic interference (EMI), and adaptability for millimeter and terahertz wave applications [2,6-10].

Advances in analytical techniques, enabled by software such as CST Studio Suite and Ansys allowed researchers to design different FSS filters. The numerical methods used for the analysis technique are the Finite Difference Time Domain (FDTD) method, Finite Element Method (FEM) and the Integral Equation Method (IEM). While the FDTD method and the FEM can be applied to any structure, they are generally relatively slow. In contrast, the IEM proves to be extremely efficient when used with basic functions for the entire domain, although it is usually limited to certain shapes. The factor that plays a role in FSS filters is their bandwidth, which is influenced by the unit cell and the substrate material. The introduction of cascade layers in FSS designs broaden the operating bandwidth, resulting in wider and more uniform insertion loss. However, the misalignment of these cascade layers can affect performance and impact parameters such as transmittance and bandwidth [4]. The overall frequency response of an FSS layered filter, which includes its bandwidth, transfer function and sensitivity to incident wave angle and polarization, is largely determined by the grating spacing between unit cells in addition to the unit cell parameters. An optimal spacing between the unit cells can increase the bandwidth and maintain a stable resonant frequency for the filter over variations in the angle of incidence [11].

Some of the research in the field of FSS filter that carried out between 2020 and 2023 are listed in the Table 1 below. This paper presents various material technologies for FSS filters, including 3D printing, ink-based methods, textile approaches and metamaterial techniques. It provides a comparative analysis of the materials and techniques for certain applications and highlights their respective advantages and limitations. The structure of the article is as follows: Section 2 deals with background knowledge, including FSS theory. Section 3 focuses primarily on the FSS fabrication material and method available in the industry, detailing the advantages and limitations of each approach. Finally, Section 4 examines the future challenges in FSS material and fabrication methods. This review paper is intended for those involved in research in the fields of telecommunications, electronics and electromagnetic engineering to have the overview on the method that used to fabricate the FSS filter.

Table 1
The various research related to Frequency Selective Surface (FSS) filter from the year 2020 until 2023

Source and year	Method	Operating frequency	Material/shape
Harnois *et al.,* (2020) [12]	Water transfer printing	-	
Ghavidel *et al.,* (2021) [4]	Photolithography method	27GHz and 16GHz	A low thickness material (RT5880)
Peralvo *et al.,* (2022) [13]	VAT photopolymerization	Millimeter-wave	Square 3D aperture

Table 1
The various research related to Frequency Selective Surface (FSS) filter from the year 2020 until 2023

Source and year	Method	Operating frequency	Material/shape
Newton *et al.,* (2022) [14]	Vanadium dioxide (VO2)	15-17 µm with a stopband center wavelength, switch between 15.5 and 16.1 µm	-
Kokkonen (2023) [15]	Coating paper with silver ink and subsequent laser etching	102, 113, and 126 GHz	Combine square and ring patches

2. Frequency Selective Surface Background

2.1 Classification

The resonant frequency of operation is governed by the design of the array element, determining whether an incoming plane wave is allowed to pass through or is obstructed. Transmission and reflection take place when the frequency of the incident radiation matches the resonance frequency of the elements constituting the FSS. This resonant behaviour can be manipulated by altering various parameters such as individual element height, geometric structure, array periodicity, substrate electromagnetic properties and FSS thickness.

The functional principle of FSS is based on capacitive and inductive elements that act as filters. FSS filters can be categorized into four types based on physical construction and geometry: High-pass, low-pass, band-pass and notch filters as shown in Figure 1. Inductive FSS, also known as apertures, are structures in which the resonant elements are cut out of a ground plane, creating a surface on which the elements are electrically connected at any point, resulting in a frequency response similar to that of high-pass or band-pass filters. Conversely, capacitive FSS complement inductive FSS, where the resonant elements are not electrically connected, resulting in a response similar to a low-pass or band-pass filters. Babinet's theorem applies when there is no dielectric and the metal plates are smaller than the operating wavelength [16].

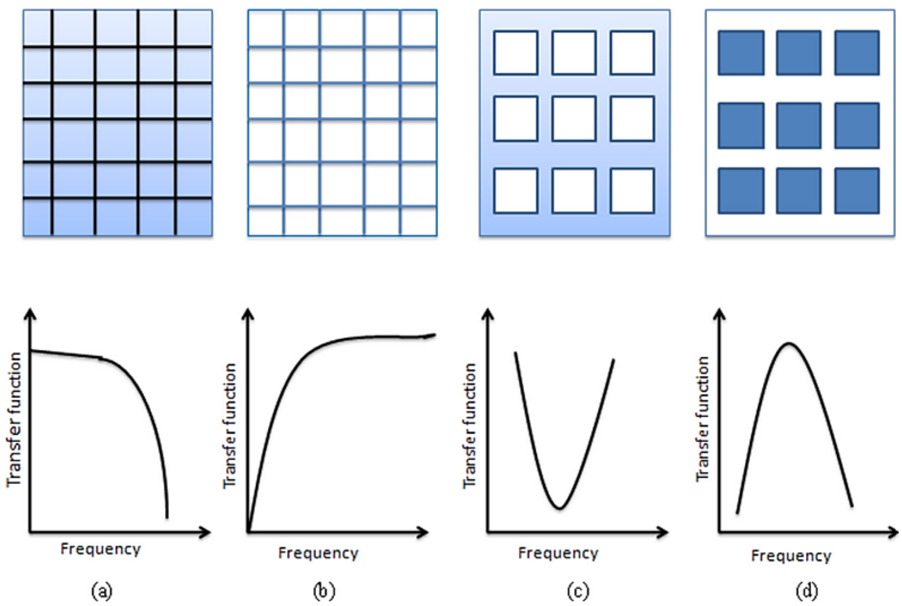

Fig. 1. Four types that can be categorized such as high pass, low pass, band pass and notch filter

2.2 Factor Affect the Performance Analysis
2.2.1 Electrical conductivity

An essential requirement across all FSS manufacturing materials is the inclusion of a highly efficient electrical conductive component. This may take the form of copper sheets embedded into dielectric substrates or silver nanoparticles mixed within inks or incorporated into textiles. Reduced conductivity directly corresponds to increased resistance to electric current flow, consequently leading to reduced transmission or reflection capabilities, especially for bandpass or band stop designs within the realm of FSS design.

2.2.2 Substrate permittivity

In FSS designs where the electrical conductive element relies on physical support from a dielectric material, the relative permittivity and thickness of the dielectric can exert a notable influence on FSS performance. The FSS frequency response is particularly sensitive to parameters such as relative permittivity (fr) and dielectric thickness (h). Changes in permittivity can significantly shift the resonance frequency for a given FSS unit-cell design. Conversely, dielectric thickness has a relatively smaller effect on resonance frequency offset, which is contingent upon the permittivity value.

2.3 Equivalent Circuit Model

Depending on its filter characteristics, an FSS operates based on a series or parallel RLC circuit. The FSS patches contribute to the resistance (R) and inductance (L), while the gaps between the FSS elements form the capacitance (C). Electrostatic principles, as they apply to the capacitance of a parallel plate capacitor and the inductance of parallel wires, provide insight into the physical interpretation of these C and L values for different FSS configurations, as shown in Eq. 1. The use of an equivalent circuit approach is invaluable for analyzing FSSs and projecting their characteristics. In this approach, two different types of elements are distinguished within an array geometry, allowing low-pass and high-pass responses. When designing FSS, the selection of a suitable array geometry is of utmost importance. Researchers have proposed numerous unit cell geometries, each offering their own advantages and strengths for controlling the properties in the desired directions.

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

3. Fabrication Technique

FSSs can be fabricated using various materials and employing multiple manufacturing techniques [17]. The aspect that terms of flexibility, operative bandwidth, efficiency, realization complexity, robustness, tuning speed, and costs. The review consists of PCB, ink, textiles and meta-metals as shown in Figure 2.

Typically, a printed circuit board (PCB) consists of copper sheets laminated to an electrically non-conductive substrate. The PCB can be categorized as single-sided (with one copper sheet), double-sided (with copper sheets on both sides of a single substrate), or multilayered (with multiple substrate and copper layers). Some of the research that have been done with different layer of PCB are listed in Table 2. The desired pattern can be created from the copper clad PCB using a subtractive method, often by milling, laser ablation or chemical etching. The chemical etching is used to improve the FSS frequency roll off factor or for multiband behavior.

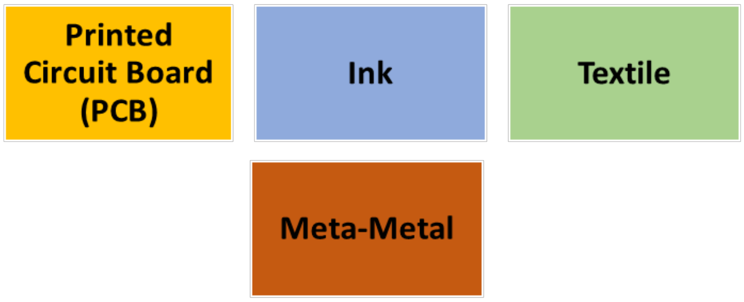

Fig. 2. The material that involved in the FSS filter fabrication such as PCB, ink, textile and meta-metal are discussed in this paper

Flexible PCB substrates such as polyester films and RO3003 offer a cost-effective solution with low transmission losses and improved flexibility. Passive FSS frequency responses can be significantly modified, either during assembly or by incorporating discrete components into the cells to enable switching and tuning functions. For fixed frequency response, surface mount device capacitors may suffice, while for active FSS, the p-i-n diodes or varactors can be soldered to the PCB. Consequently, some researchers design the bias grid on the same layer known as 2D FSS because they are constructed from thin copper sheets and a substrate. For multiple layers used for it will form a 3D FSS that can enhance frequency response and angular stability [18].

In communication systems requires good electrical performance for a narrow band. The electrical performance and mechanical properties can be improved by embedding the FSS structure. The FSS is produced with an e-beam evaporator that give advantage for curved surfaces. The multilayer FSS consists of patch-grid type copper layers as capacitive and inductive surface on the pre-impregnated glass/epoxy layer (GFRP, glass fibre reinforced plastic), and the copper layers are formed by e-beam deposition on the GFRP layer [19].

Table 2
The various research related single layer and double layer for the FSS filter that using the PCB

Author	Single layer/double layer	Material	Operating frequency
Huang *et al.,* [20]	Single-layer dual-band		0 to 4.7 GHz and 25.3 to 30.0 GHz
Kanchana *et al.,* [21]	Single-layer	PCB FR4	4.85 GHz to 17.23 GHz
Paul *et al.,* [22]	Single-layer	PCB FR4	2.8–17.1 GHz
Gao *et al.,* [23]	Double layer		Tera Hz bandpass filter

3.1 Ink

Electrically conductive ink has emerged as an alternative method for the fabrication of FSS, as shown by several authors in Table 3 using different materials. Metal nanoparticle-based inks are versatile and can be used on various substrates such as paper, glass, various polyester materials such as polyethylene naphthalate and polyethylene terephthalate (PET), as well as solid (3D-printed) objects that can be coated with these inks. Two methods of applying ink can be applied, such as applying ink to a solid object by brush or spray and the other method is additive manufacturing techniques using conductive inks. The other techniques that can be used are inkjet printing, lithographic processes, and roll-to-roll (R2R) printing technologies. The roll-to-roll printing technology has the advantage of cost saving and high yield. A common ink used in both research and commercial applications is silver nanoparticle ink, which is known for its exceptional conductivity among metals and is widely available in the form of inkjet printers. Recent advances have resulted in stable formulations that deliver reproducible printing characteristics on a variety of substrates.

The inkjet production of FSS has been thoroughly investigated, especially when the FSS was printed on a paper substrate with an inorganic, microporous receiving layer. Factors such as the number of layers applied and the ability to apply droplets as needed allowed the original design of the FSS array elements to be altered by reducing the amount of conductive material applied. The single-layer thin lines were prone to discontinuities, especially in frame elements which can be solved by adding additional layers of paint. Compared to an FSS etched on a printed circuit board, the printed prototype exhibited lower frequency transmission (due to differences in substrate thickness and relative permittivity), while it showed similar insulation performance with three layers of conductive ink.

Table 3
The various research related to frequency selective surface filter using ink or inkjet printing technique

Author	Material for conductive element
Kokkonen *et al.,* [15]	Coating paper with silver ink
Esquita *et al.,* [24]	Conductive ink
Yong *et al.,* [25]	Inkjet printing
Turki *et al.,* [26]	Inkjet printing

3.2 Textile

Nowadays, much attention is being paid to conductive materials made from textiles due to growing fascination with wearable technologies and applications in communications, sensing and electromagnetic shielding. Electromagnetic structures utilizing conductive textiles offer several advantages such as light weight, flexibility, softness, and a high strength-to-weight ratio. Some researchers are exploring the fusion of traditional textile fabrication methods (using non-conductive materials) with engineered materials that possess electromagnetic properties, taking an interdisciplinary approach to create a network with conductive properties. In addition, this type of FSS benefits from the integration of advanced manufacturing techniques such as computerized knitting, embroidery and weaving machines, as shown in Table 4. These machines can consistently produce predetermined geometries for large-scale solutions and a variety of 3D configurations. Other manufacturing techniques for textile-based FSS include screen printing and hand weaving.

In addition, fabric surfaces are treated with conductive coatings and deposits by methods such as dip coating or vacuum deposition. Flexible substrates, such as polymer-based fabrics, improve flexibility. Functional conductive textiles can be integrated into composite structures, providing a lightweight and flexible alternative to PCB-based structures. In addition, the integration of FSS into textile antennas enables their use in portable communication devices. Applications of flexible textile screen substrates extend to wearable technology and health monitoring. For example, a new flexible and wearable geometry has been developed and tested for monitoring high temperatures in humans in the C-band. This highlights the importance of designs that balance flexibility and durability to withstand the typical movement and wear and tear of textiles. Ensuring washability is critical to maintaining FSS functionality after washing.

A disadvantage of using textile especially for complex structures FSS time consuming and not suitable for mass production. This is due to difficulty to cut into complex shape and to attach on the non-conductive textile substrate using adhesives. The alternative for these drawbacks is computerized embroidery uses a conductive thread to embroider conductive features, such as a patch antenna, onto a non-conductive textile substrate. Although computerized embroidery is advanced in manufacturing, the process is slow and the conductive surfaces produced poor continuous conductivity. The development of textile-based FSS is challenging due to the choice of substrate and availability on the market. Advances in the fibers used to make comfortable clothing that can withstand fabrication temperatures must be considered.

Table 4
The various research related textile and using different fabrication method such as embroidy

Author	Fabric	Application	Operating frequency
Whittow *et al.,* [27]	Inkjet printing technique	-	
Rumijowska *et al.,* [28]	Textile and film substrate	Shielding	
Hesarian *et al.,* [29]	Fabric-embroidery method	Shielding	1805-1880 MHz
Üner *et al.,* [30]	Textile fabric-embroidered		GSM, Wi-Fi, LTE, and WiMAX
Rahayu *et al.,* [31]	Textile	Detection breast tumor	

3.3 Metametal

Metamaterials (MTMs) are artificially engineered materials with unique electromagnetic properties not occurring in natural materials. MTMs have gained considerable attention owing to theirexotic electromagnetic characteristics such as negative permittivity and permeability, thereby a negative refraction index. Metamaterials are often used in applications such as subwavelength resolution imaging, transmitters, filters, wireless communication and absorbers. Subwavelength resonators have been explored to achieve specific frequency responses, but their resonant frequencies are typically limited to certain regions due to fixed geometries. To improve the flexibility of these structures and their response characteristics, various frequency tuning mechanisms have been investigated (see Table 5). Metamaterial-based FSS were investigated in which liquid metal was inserted into a pattern aligned in the form of stretchable devices such as electrical connections, wires and skin sensors. An I-shaped FSS exhibited negative permittivity and permeability properties in the C- and S-band frequency ranges.

Table 5
The various research related to frequency selective surface filter using the metamaterial

Author	Material	Operating frequency
Atrakchii *et al.,* [32]	Metamaterial	Wi-MAX 3.5 GHZ (reject)
Zeng *et al.,* [33]	Metamaterial	-
Oliveri *et al.,* [34]	Metamaterial	
Yang *et al.,* [35]	Metamaterial	1.20 GHz to 2.63 GHz and 2.0 GHz to 5.9 GHz
Bharti *et al.,* [36]	Metamaterial	

The concept of a substance capable of absorbing all radiation waves, regardless of frequency or angle of incidence, was introduced a century ago by Planck's law. For practical applications of metamaterial as absorbers on uneven structures, the structure must be independent of polarization and angle of the incident waves. This can be achieved by using symmetrically arranged metallic arrays on the surface of the absorber. Traditionally, absorbers have a sandwich structure with multiple layers where the absorption varies with the angle of incidence for both TE and TM modes. Some studies have shown that increasing the angle of incidence impairs impedance matching, resulting in higher reflection and lower absorption rates. Consequently, it has been a challenge to develop a low-cost, polarization-insensitive absorber that can operate efficiently at large angles of incidence. Each of the advantage and disadvantages of the fabrication method is outlined in Table 6.

Table 6
The advantages and disadvantages of each fabrication methods

Fabrication method	Advantages	Disadvantages
Printed circuit board (PCB)	i. Flexible PCB substrates such as polyester films and RO3003 offer a cost-effective solution with low transmission losses and improved flexibility. ii. Passive FSS frequency responses can be significantly modified, either during assembly or by incorporating discrete components into the cells to enable switching and tuning functions. iii. Fixed frequency response, surface mount device capacitors may suffice, while for active FSS, the p-i-n diodes or varactors can be soldered to the PCB.	i. Some of the manufacturing process of PCBs involves chemicals that can have negative environmental impacts, including waste disposal issues and pollution from hazardous materials. ii. Rigid PCBs provides lack flexibility unsuitable for applications that require bending or moving parts.
Ink	i. The roll-to-roll printing technology has the advantage of cost saving and high yield. ii. Stable formulations forreproducible printing characteristics on a variety of substrates. iii. Exhibited lower frequency transmission (due to differences in substrate thickness and relative permittivity), while it showed similar insulation performance with three layers of conductive ink.	i. The single-layer thin lines were prone to discontinuities, especially in frame elements which can be solved by adding additional layers of paint
Textile	i. Light weight, flexibility, softness and a high strength-to-weight ratio. ii. Flexible substrates, such as polymer-based fabrics, improve flexibility. iii. balance flexibility and durability to withstand the typical movement and wear and tear of textiles	i. For complex structures FSS time consuming and not suitable for mass production. ii. Computerized embroidery is advanced in manufacturing, the process is slow and the conductive surfaces produced poor continuous conductivity.
Metametal	i. Negative permittivity, a negative refractive index and an index close to zero. ii. Application for subwavelength resolution imaging, transmitters, filters, wireless communication and absorbers	i. Narrow bandwidth, high losses, and tolerance sensitivity)

4. Future Challenges

4.1 Material Selection

The material for the dielectric substrate must be transparent to allow sufficient absorption and have a considerable thickness to reduce dielectric losses and dispersion. The choice of conductive material is influenced by the conductivity and width of the material, which have a significant impact on the performance of the FSS. The common metals used are aluminium and copper, both have low conduction losses due to their high conductivity and are readily available. Aluminium is preferred over copper because it facilitates fabrication in the Tera Hz range [31].

4.2 Integration with Flexible Substrates

As the demand for flexible systems increases, the integration of FSS into flexible substrates poses challenges in terms of fabrication compatibility and mechanical reliability. The challenge face is the FSS openings need to be as narrow as possible for better thermal insulation. The coating must be carefully etched to avoid thermal insulation degradation and maintain the aesthetics of the window glass. The misalignment of patch and grid, the size of the fibre substrate (FSS) and differences in thickness contribute to the discrepancies between the measured and simulated results. Due to their differently curved surfaces, conventional FSS produced on real structural surfaces have their limitations.

4.3 Fabrication Technique

The photolithographic technique is suitable for the frequency range 100-200 GHz. This technique involves dry and wet etching, depending on the material to be etched, the critical dimensions and the application. Dry etching is more expensive and complex than wet etching, but the advantage is be able control critical dimensions. For the frequency above 200 GHz, under-etching effects occur and the reproduction of the contour of the small openings in the etched metal foil is impaired. It can be solved using the electroplating method that is useful for the fabrication of FSS for frequency ranges between 200 GHz and 1 THz. A bandpass FSS filter in cross-shaped with copper substrate was fabricated using galvanic growth at 280 GHz acquires accurate frequency response.

4.4 Miniaturization

The move towards smaller electronic devices presents hurdles in crafting FSS filters with tiny details and high ratios. The new technology for miniature includes the wearables and IoT gadgets. In addition, compact FSS filters must be able to do multitask such as filtering, steering beams, and altering polarization. This demands intricate FSS setups while staying compact and effective. Leveraging new materials like metamaterials, graphene, and 2D materials could boost FSS filter performance, but integrating them into practical manufacturing methods with reliability and affordability is still difficult.

4.5 Manufacturability and Cost

Ensuring that FSS filters meet performance standards while also being manufacturable and cost-effective is crucial for widespread adoption. The choice of fabrication techniques must be of producing high-performance FSS filters at a low cost, utilizing readily available materials and scalable processes, to ensure commercial viability. Thermoforming technology proves effective in creating large-area interconnected circuitry that molds proposed components into 3D shapes using patterns crafted on a flat substrate. Following this, thermoforming is applied to the flat circuit to achieve the desired 3D configuration. Researchers have explored this approach using water transfer printing (WTP) technology for antenna radome applications in the 8.1-9.1 GHz range. This technique is particularly suitable for FSS filters with semi-spherical shapes.

5. Conclusions

In conclusion, the findings of this research are different fabrication material/methods have the advantages and the drawbacks and basically the selection of the method is depending on the applications and desired characteristic. The fabrication method is chosen based on the intended applications and desired characteristic. For example, FSS filter used in communication system have the characteristic to control and manipulate electromagnetic waves, allowing certain frequencies to pass through while blocking others. There are several fabrication techniques for FSS filters, and the choice often depends on factors such as the desired frequency range, material properties, and the complexity of the filter structure. Some common fabrication methods include photolithography, etching, printing or deposition. The choice of fabrication method depends on factors such as the required performance, cost, scalability, and the properties of the materials involved. Researchers and engineers select the most appropriate method based on these considerations to fabricate FSS filters tailored to specific applications. Some of the application required material that can bend or flexibility, thus flexible substrates such as polyethylene terephthalate (PET), polyimide (PI), or flexible glass is used. Fabrication techniques such as photolithography, etching, or deposition can then be adapted to suit these flexible substrates.

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References

[1] Sanz-Izquierdo, Benito, and Edward A. Parker. "3-D printing of elements in frequency selective arrays." *IEEE Transactions on Antennas and Propagation* 62, no. 12 (2014): 6060-6066. https://doi.org/10.1109/TAP.2014.2359470

[2] Anwar, Rana Sadaf, Lingfeng Mao, and Huansheng Ning. "Frequency selective surfaces: A review." *Applied Sciences* 8, no. 9 (2018): 1689. https://doi.org/10.3390/app8091689

[3] Kapoor, Ankush, Ranjan Mishra, and Pradeep Kumar. "Frequency selective surfaces as spatial filters: Fundamentals, analysis and applications." *Alexandria Engineering Journal* 61, no. 6 (2022): 4263-4293. https://doi.org/10.1016/j.aej.2021.09.046

[4] Ghavidel, A., M. Kokkonen, and S. Myllymäki. "A double layer FSS filter for sub-THz applications." *Scientific Reports* 11, no. 1 (2021): 19773. https://doi.org/10.1038/s41598-021-99256-2

[5] Nemat-Abad, Hamed Mohammadi, Ehsan Zareian-Jahromi, and Raheleh Basiri. "Design and equivalent circuit model extraction of a third-order band-pass frequency selective surface filter for terahertz applications." *Engineering Science and Technology, an International Journal* 22, no. 3 (2019): 862-868. https://doi.org/10.1016/j.jestch.2019.01.008

[6] Panwar, Ravi, and Jung Ryul Lee. "Progress in frequency selective surface-based smart electromagnetic structures: A critical review." *Aerospace Science and Technology* 66 (2017): 216-234. https://doi.org/10.1016/j.ast.2017.03.006

[7] Tong, Xingcun Colin, and Xingcun Colin Tong. "Metamaterials inspired frequency selective surfaces." *Functional Metamaterials and Metadevices* (2018): 155-171. https://doi.org/10.1007/978-3-319-66044-8_8

[8] Bayatpur, Farhad. "Metamaterial-Inspired Frequency-Selective Surfaces." PhD diss., 2009. https://doi.org/10.1109/TAP.2008.2011404

[9] Emara, Hesham, Sherif El Dyasti, Hussein Ghouz, and Mohamed Abo Sree. "Design of a compact dual-frequency microstrip antenna using DGS structure for millimeter-wave applications." *Journal of Advanced Research in Applied Sciences and Engineering Technology* 28, no. 3 (2022): 221-234. https://doi.org/10.37934/araset.28.3.221234

[10] Taher, F., Mohamed Fathy Abo Sree, Hesham A. Mohamed, Hussein Hamed Ghouz, and Sarah Yehia Abdel Fatah. "Design and fabrication of compact MIMO array antenna with tapered feed line for 5G applications." *Journal of Advanced Research in Applied Sciences and Engineering Technology* 46, no. 1 (2025): 146. https://doi.org/10.37934/araset.46.1.146156

[11] Chu, Julio. *Experimental surface pressure data obtained on 65 delta wing across Reynolds number and Mach number ranges*. 3. National Aeronautics and Space Administration, Langley Rearch Center, 1996.
[12] Harnois, Maxime, Mohamed Himdi, Wai Yan Yong, Sharul Kamal Abdul Rahim, Karim Tekkouk, and Nicolas Cheval. "An improved fabrication technique for the 3-D frequency selective surface based on water transfer printing technology." *Scientific Reports* 10, no. 1 (2020): 1714. https://doi.org/10.1038/s41598-020-58657-5
[13] Vásquez-Peralvo, Juan Andrés, Adrián Tamayo-Domínguez, Gerardo Pérez-Palomino, José Manuel Fernández-González, and Thomas Wong. "3D inductive frequency selective structures using additive manufacturing and low-cost metallization." *Sensors* 22, no. 2 (2022): 552. https://doi.org/10.3390/s22020552
[14] Newton, Lucas, and Niru K. Nahar. "Reconfigurable far-infrared FSS filters on polyimide substrate." *Journal of Infrared, Millimeter, and Terahertz Waves* 44, no. 11 (2023): 885-897. https://doi.org/10.1007/s10762-023-00953-y
[15] Kokkonen, Mikko, Rakshita Dessai, and Sami Myllymäki. "Implementation of a second-order frequency selective surface filter at mmWave using paper and silver ink." *The Journal of Engineering* 2023, no. 4 (2023): e12249. https://doi.org/10.1049/tje2.12249
[16] Munk, Ben A. *Frequency selective surfaces: theory and design*. John Wiley & Sons, 2005.
[17] Yang, Jianfeng, Juan Chen, Lei Quan, Zhenzhen Zhao, Hongyu Shi, and Yajun Liu. "Metamaterial-inspired optically transparent active dual-band frequency selective surface with independent wideband tunability." *Optics Express* 29, no. 17 (2021): 27542-27553. https://doi.org/10.1364/OE.434262
[18] Costa, Filippo, Agostino Monorchio, and Giuliano Manara. "An overview of equivalent circuit modeling techniques of frequency selective surfaces and metasurfaces." *The Applied Computational Electromagnetics Society Journal (ACES)* (2014): 960-976.
[19] Kim, J., J. Jeong, P. Qiao, Z. Shan, and W. Hwang. "Fabrication method of frequency selective surface for communication system with 3-dimensional structure." In *Fifth Asia International Symposium on Mechatronics (AISM 2015)*, p. 1-3. IET, 2015. https://doi.org/10.1049/cp.2015.1570
[20] Huang, Yu, Liping Yan, Xiang Zhao, Ming Ye, and Richard Xian-Ke Gao. "A single-layer dual-band frequency selective surface for 5G shielding." In *2022 International Symposium on Electromagnetic Compatibility–EMC Europe*, p. 683-686. IEEE, 2022. https://doi.org/10.1109/EMCEurope51680.2022.9901163
[21] Kanchana, D., S. Radha, B. S. Sreeja, and E. Manikandan. "A single layer UWB frequency selective surface for shielding application." *Journal of Electronic Materials* 49 (2020): 4794-4800. https://doi.org/10.1007/s11664-020-08210-x
[22] Paul, Gouri Shankar, Kaushik Mandal, and Ali Lalbakhsh. "Single-layer ultra-wide stop-band frequency selective surface using interconnected square rings." *AEU-International Journal of Electronics and Communications* 132 (2021): 153630. https://doi.org/10.1016/j.aeue.2021.153630
[23] Gao, Tao, Feng Huang, Yanqing Chen, Weilin Zhu, Xuewei Ju, and Xiangfeng Wang. "Resonant coupling effects in a double-layer THz bandpass filter." *Applied Sciences* 10, no. 15 (2020): 5030. https://doi.org/10.3390/app10155030
[24] Mesquita, Marcelo David S., Adaildo Gomes D'Assunção, João Bosco L. Oliveira, and Yuri Max Vieira Batista. "A new conductive ink for microstrip antenna and bioinspired FSS designs on glass and fiberglass substrates." *Journal of Microwaves, Optoelectronics and Electromagnetic Applications* 18, no. 2 (2019): 227-245. https://doi.org/10.1590/2179-10742019v18i21554
[25] Yong, Wai Yan, Sharul Kamal Abdul Rahim, Mohamed Himdi, Fauziahanim Che Seman, Ding Lik Suong, Muhammad Ridduan Ramli, and Husameldin Abdelrahman Elmobarak. "Flexible convoluted ring shaped FSS for X-band screening application." *IEEE Access* 6 (2018): 11657-11665. https://doi.org/10.1109/ACCESS.2018.2804091
[26] Turki, Badredin M., Edward Ted A. Parker, Sebastian Wünscher, Ulrich S. Schubert, Rachel Saunders, Veronica Sanchez-Romaguera, Mohamad Ali Ziai, Stephen G. Yeates, and John C. Batchelor. "Significant factors in the inkjet manufacture of frequency-selective surfaces." *IEEE Transactions on Components, Packaging and Manufacturing Technology* 6, no. 6 (2016): 933-940. https://doi.org/10.1109/TCPMT.2016.2561972
[27] Whittow, William G. "3D printing, inkjet printing and embroidery techniques for wearable antennas." In *2016 10th European Conference on Antennas and Propagation (EuCAP)*, p. 1-4. IEEE, 2016. https://doi.org/10.1109/EuCAP.2016.7481266
[28] Rac-Rumijowska, Olga, Piotr Pokryszka, Tomasz Rybicki, Patrycja Suchorska-Woźniak, Maksymilian Woźniak, Katarzyna Kaczkowska, and Iwona Karbownik. "Influence of flexible and textile substrates on Frequency-Selective Surfaces (FSS)." *Sensors* 24, no. 5 (2024): 1704. https://doi.org/10.3390/s24051704
[29] Hesarian, Mir Saeid, Saeed Shaikhzadeh Najar, and Reza Sarraf Shirazi. "Design and fabrication of a fabric for electromagnetic filtering application (experimental and modeling analysis)." *The Journal of the Textile Institute* 109, no. 6 (2018): 775-784. https://doi.org/10.1080/00405000.2017.1369346

[30] Üner, İbrahim, Sultan Can, Banu Hatice Gürcüm, Asım Egemen Yılmaz, and Ertugrul Aksoy. "Design and implementation of a textile-based embroidered frequency selective surface." *Textile and Apparel* 32, no. 4 (2022): 297-303. https://doi.org/10.32710/tekstilvekonfeksiyon.956310

[31] Rahayu, Yusnita, M. Khairon, Khairul Najmy Abdul Rani, and Teguh Praludi. "Detection of breast tumour depth using felt substrate textile antenna." *Journal of Advanced Research in Applied Sciences and Engineering Technology* 39, no. 1 (2024): 59-75. https://doi.org/10.37934/araset.39.1.5975

[32] Al-Atrakchii, Mamoon, Khalil Sayidmarie, and Raed Abd-Alhameed. "Frequency selective surface using the metamaterial property of the U-shaped strip." In *Proceedings of the 1st International Multi-Disciplinary Conference Theme: Sustainable Development and Smart Planning, IMDC-SDSP 2020, Cyperspace, 28-30 June 2020*. 2020. http://dx.doi.org/10.4108/eai.28-6-2020.2297892

[33] Zeng, Yifan, Zhe Chen, Wanhong Luo, Chaoyi Sun, Yuyuan Zhao, and Lu Zhang. "Design of a metamaterial bandpass filter in the terahertz region." In *2022 International Applied Computational Electromagnetics Society Symposium (ACES-China)*, p. 1-3. IEEE, 2022. https://doi.org/10.1109/ACES-China56081.2022.10064909

[34] Oliveri, Giacomo, Douglas H. Werner, and Andrea Massa. "Reconfigurable electromagnetics through metamaterials—A review." *Proceedings of the IEEE* 103, no. 7 (2015): 1034-1056. https://doi.org/10.1109/JPROC.2015.2394292

[35] Bharti, Garima, Kumud Ranjan Jha, and G. Singh. "Terahertz frequency selective surface for future wireless communication systems." *Optik* 126, no. 24 (2015): 5909-5917. https://doi.org/10.1016/j.ijleo.2015.09.038

[36] Li, Liyang, Jun Wang, Mingde Feng, Hongliang Du, Hua Ma, Jiafu Wang, Jieqiu Zhang, and Shaobo Qu. "All-dielectric frequency selective surface based on 3D printing materials." *Physica Status Solidi (a)* 215, no. 14 (2018): 1700840. https://doi.org/10.1002/pssa.201700840