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Active frequency selective surfaces: a systematic review for sub-6 GHz band

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Review Paper

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Abstract

Radar absorption structures made of an active frequency selective surfaces (AFSS) have enormous potential in the aviation, naval, and other industries. In this research paper, a systematic review (SR) is carried out in the field of the AFSS to bring uncertainties, obstacles, challenges, classifications, applications, and design issues that arrive in the development of the sub-6 GHz architecture. To bias the AFSS component, as per the signal requirements, a unique set of circuits (PIN diode) is required, with ON and OFF state and a transmission zone. The bandwidth of which is determined by the bias voltage supplied. It can behave as a complicated hybrid impedance structure by providing ON and OFF biasing voltage to a PIN diode embodied in an FSS structure. Higher manufacturing costs of AFSS components, more significant complexities involved, a large amount of power consumption, and reactive impedance losses are some common limitations faced while implementing and designing an AFSS. Many envisioned problems are corrected with the AFSS design, current or creative implementations, and processing parameters are investigated progressively. It implies that new AFSSs will be an alternative to regular FSSs in the future. This paper is based on Kitchenham's three-phase review procedure and supplements it with results, views, and recommendations from other leading experts in the field.

Introduction

Metasurfaces (MS) are planar metamaterials with a subwavelength thickness created via nanoprinting and lithography. Controlling spatially changing electromagnetic (EM) or optical responses, including scattering phase, amplitude, and polarization, is possible. The ultra-thin construction of MSs can significantly reduce deleterious and unwanted wave propagation losses through careful material and design selection. Regarding polarization response, all metasurfaces are classified as high-impedance surfaces (HIS), frequency selective surfaces (FSS), ideal absorbers, and reflecting surfaces are fundamental periodic structures made of aperture elements or conductive patches meant to reflect, transmit, or absorb EM waves that are known as finite-state systems [1].

An FSS is proficient in transmitting or preventing waves of specific wavelengths; as a result, the FSS structure is referred to as physical filtration in EMs. The present-era telecommunication system advancements necessitate the development of unique designs of FSS to comply with rigorous EM criteria [2, 3], absorption of microwaves [4, 5], lowering of radar cross-sections (RCSs), elimination of electromagnetic interference (EMI), millimeter and terahertz pulse activities, and other FSS applications are few such examples [1]. Moreover, regarding the unprecedented attention generated by extraordinary broadcasting, meta-surfaces, and associated challenges, in the last few years, considerable studies have been performed on various kinds of traditional EM structures related to FSS. These developments have a long history in electronics, nanotechnology, electrical engineering, and physics. Although traditional FSSs have restricted use due to low-frequency bands and poor filtration sensitivity that fall short of the operational demands for the contemporary EM applications, a wide range of solutions for improving the properties of classic FSSs are available in the open literature and on the internet. Activated fractal 3D FSS, FSSs, and FSSs-based EM structures are only a limited number of the most recent techniques that academics have advanced.

Additionally, metamaterials are the subject of study now [6, 7], miniaturized FSSs [8, 9], and embedded sandwiched FSSs [10–20]. It can represent a significant advancement in radiofrequency technology. However, some applications necessitate that the passband/stopband frequency of the FSS is changeable under certain situations, and as a result, the active FSS study has been warmly embraced [21–28].

Methodology

The technique described in the systematic review (SR) is based on "Preferred Reporting Items for Systematic Reviews and Meta-Analyses" (PRISMA) declarations. PRISMA is the minimal collection of SRs and meta-analyses related to evidence. It intends to report studies that assess the impacts of interventions. However, it can also be utilized to record SRs with objectives other than evaluating interventions for prevalence, diagnosis, or prognosis.

Search strategy

As a part of this work, a systematic literature review focusing on FSSs and active frequency selective surfaces (AFSSs) structures is studied to better understand the development of AFSSs. The search strategy involved a blind focus to-FSS database search, a citation AFSS, and a citation sub-6 GHz. The initial information sources consist of four primary Academic Literature Collections: Science Direct, IEEE, Springer, and Scopus databases [29–36], which assist in finding the objective of this review as well as the research questions.

The AFSS is an emerging field of research. This work systematically focuses on a detailed study of the Challenges, Classification, Application, and Design Issues of AFSS for the sub-6 GHz frequency bandwidth (BW). Scientists need to pay more attention to a comprehensive analysis of the numerous varieties of FSSs that have emerged, differentiated by their structural design, uses, and the behavior of the array of elements used. Instead, they have taken this omission for allowed.

Because of this, this review paper presents an overview of the rapidly increasing study field of AFSSs by evaluating advancements over the last few years, with a primary focus on categorizing the FSSs.

A further goal of this SR is the development of an open-source knowledge platform to support future research on this topic by collecting and analyzing critical findings from the previous study, summarizing and comparing them, and by identifying the issues and limitations that have arisen from the research. In the context of the extensive research on FSS, the following study topics are addressed:

RQ 1: Why is there a worldwide need for FSSs and AFSSs?

RQ 2: What are the types of FSS, and in what way does AFSS relate to FSS and its classification?

RQ 3: What are the challenges in implementing AFSS in the concern area of sub-GHz?

RQ 4: What are the design issues in developing AFSS for sub-6 GHz for future perspective?

RQ 5: How does the future of AFSSs reflect their durability and efficiency?

Classification of AFSS

The AFSS is a good option for overcoming the constraints of FSS as a superstrate. Incorporation of the lumped-element devices in FSS provides various advantages, including increased radiation BW, control of resonance frequency and directivity, and many more. The working capabilities of AFSS depend upon the construction of the frequency-selective surface. Based on the surface's construction, design, structure, etc., the AFSS is classified into different categories, as discussed in Fig. 1 [37].

Based on AFSS element type

The grade of an element depends on the fundamental application of the selective surface. However, certain features stand out as being desirable for most applications. First, a quality element should have a stable, resonant frequency with an angle of incidence. Leading candidates with this feature are all the members of group 2, namely the loop categories like the 3 and 4 leg-loaded elements, the simple square and circular loops, and the hexagon element for broadband applications. It has been further observed that the "shaping" of these loops can give the designer a broad variety of BW from the narrow (the 4- and 3-legged loaded element) to a super-wide (hexagon). Although all selective surfaces can change BW by variation of the inter-element spacings, the four-legged and three-legged components can vary by changing the elements themselves. Typical for most of these elements is the onset of the second resonance for parallel polarization and oblique incidence. That leads to nulls as low as only half the octave over a fundamental frequency [38].

However, by packing the elements very close together, it is possible to experience huge BW and obtain modal interaction nulls so narrowly that they are relatively inconsequential for many applications. The square spiral element is exciting because it can reflect, but it can also be transparent. It has a very large BW approaching that of the hexagon element. It is the best center-connected element for many applications. However, the BW varies more with the change in polarization than in the hexagon case. That may or may not be advantageous for some applications [39]. However, it is possible to place several layers of FSS precisely positioned to each other, leading to the so-called super-dense surfaces. It can lead to a considerable rise in the −3 dB BW, but the modal interaction null is moved slightly upward in the frequency.

The great advantage of super-dense surfaces lies in their potential for extremely low cross-polarization. Decreasing end-loading moves the null downward while increasing the length of an end-loading moves the null upward. However, end bars themselves will eventually start to scatter. The solid internal or the plate type element is seldom applied alone but mainly with "complementary" FSS adjacent to it. Finally, the sequence of elements list is endless and expands longer every day [31]. The lumped element, when embodied, improves the response of the FSS. The AFSS enhances the sensitivity of the frequency response.

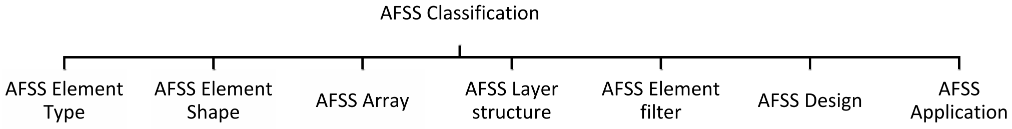

Figure 1. AFSS classification.

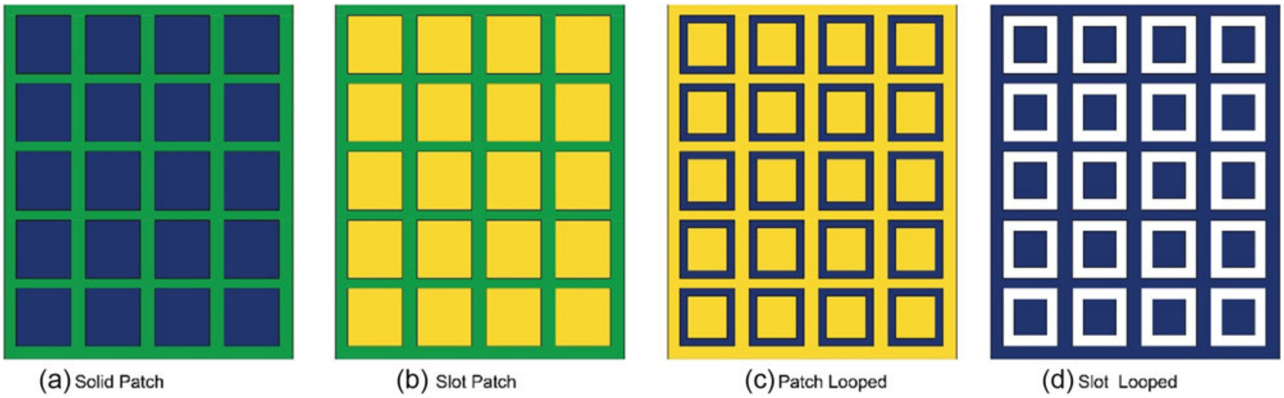

Figure 2. Type of loops.

However, fabrication errors and insertion loss arise due to localized electric fields.

Equivalent filter banks

Wu et al. [40] pioneered intrinsic mode functions (IMFs) empirical mode decomposition (EMD) statistics analysis on only White-Gaussian Noise. Fractional Gaussian noise (FGN) has been applied to show how EMD behaves as flexibilities for Gaussian broadband noise with no frequent prevailing band in stochastic situations. Similarly, a numerical simulation based on FGN is used to analyze whether the local mean decomposition technique has a wavelet-like filtering characteristic. As a result, a study has been done in previous works, and variational mode decomposition statistics are helpful. The increment method of fractional Brownian motion in time series was described as the FGN [41]. The Hurst exponent ($0 < H < 1$) is used to compose an FGN time-series autocorrelation sequence. The specific property of FSSs is that it only achieves resonance at a required frequency when the slot size or patch in the unit cell is at least half wavelength. Its constraint is solved by decreasing an electrical dimension of the forming inclusions to the sub-wavelength levels, ensuring insensitivity to changes in incidence angle and polarization [33–35].

Based on the AFSS array

The array is termed a collection of a fixed number of elements in a particular sequence, wherein all elements have the same data type. Each element is selected by one or more indices that can be computed at run time during task execution. Elements based on arrays are classified as solid patch array elements, slot array elements, patched looped array elements, and slot looped array elements, as shown in Fig. 2 [42, 43].

Based on the AFSS applications

The use of AFSS for RF interference mitigation [44] and EM shielding applications is becoming more prevalent. To address forthcoming difficulties, the applications require frequency agility. The frequency-tuning characteristics of AFSS make it appropriate for use in the adaptive environment [44–57].

Slot active frequency selective surface (SAFSS) is suggested as a low-cost twin spectrum monitoring transceiver, with every unit cell on the board having two different slots working at frequencies of 1.5 and 2.45 GHz. In every channel, certain capacitors were used to provide an appropriate single mode [58]. A 2.5D miniaturized multifunction AFSSs are designed to get polarization symmetry where four subcells of similar type are combined. Studies at harmonic wavelength may be used to understand better the fundamental surface flow and EM cluster allocation [13]. The bi-state interweaving spiral that can be reconfigured with PIN diodes in both dual-polarized and single-polarized unit cell architectures allows the EM intervention to be switched either transparent or reflective as needed at various wavelengths, allowing FSSs to transition between transparent and reflecting modes [59]. The AFSS having a squared aperture, using PIN diodes, has been analyzed by using dc bias to it. The EM properties of the AFSS structure are changed [60]. Two cascaded FSS modeled with intervening dielectrics are modeled, and the results demonstrate that switching between robust transmission and reflection of incoming EM waves is feasible [61].

AFSS with rectangular loops and AFSS with sparse active devices are investigated. The surface's frequency response may be electrically switched per waveguide simulation [23]. A configurable band stops FSS design for unlicensed 2.4 and 5.8 GHz industrial, medical, and scientific bands. A novel hypothesis utilizing PIN diodes in a high current density position is observed to achieve the desired frequency switch performance [58]. A new intelligent wall approach with the AFSS and the sensors is suggested, and intelligent walls positively impacted system performance is shown [62]. The single PIN-based diode with a bare microstrip transmission patch as a unitary component is designed as an AFSS based high-quality programmable filtering transmitter [63]. The Wi-Fi AFSS and long-term evolution-AFSS built of half-blocking transmissions at 2.45 and 2.1 GHz using cyclical looping patching and single loop patch is proposed. To be aware of the alterations between reflection characteristics and transmission characteristics, AFSSs use PIN diodes [64, 65].

Experimental demonstrations show a cord active second-order bandpass wavelength selecting surface-fed transmitter and a programmable optical transmitter and receiver beam. With the use of microwave varactors in FSS unitary cells, a DC voltage can be used to change the wavelength of the wave signal FSS between 4.0 and 5.8 GHz [13]. Researchers demonstrated an AFSS with a single-layer bandpass built on four PIN diodes and a circular loop aperture per unitary cell. This structure has an excellent transverse electric incidence angle consistency at 2.45 GHz working BW [66]. A technique for AFSS slot arrays is described. A thin,

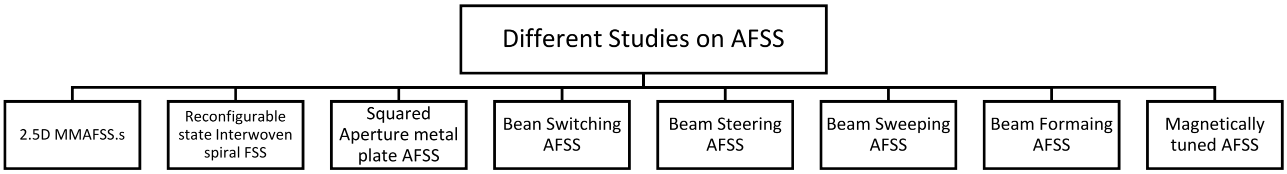

Figure 3. AFSS-based different studies.

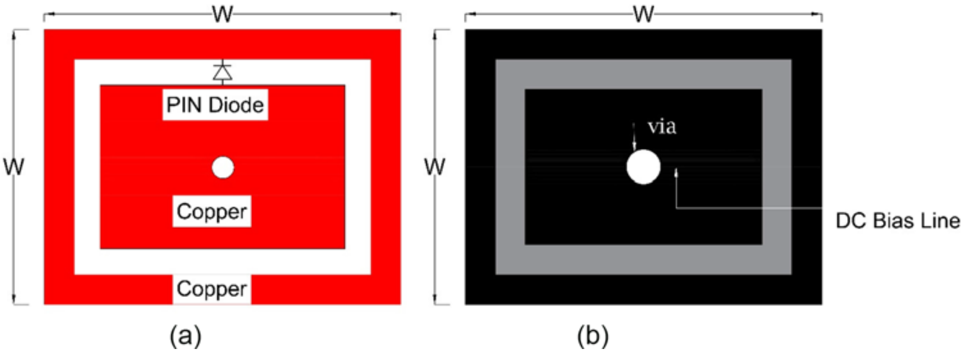

Figure 4. AFSS unitary cell configuration: (a) front side and (b) backside.

flexible substrate separates the biasing layer from the slot layer, and PIN and varactor diode (VD) type diodes are used for switching and tuning. One use is changing the environment management design of buildings to provide access to desired frequency bands [52]. Based on a transverse wave formulation and acquisition of data on the interface, the wave concept iterative process (WCIP) is developed. As a result, no matrix inversion is needed, and convergence is guaranteed regardless of the structure's interfaces. The existing intensity and electric field on the interface are solved using the technique provided.

Studies based on different designs of AFSS

AFSS has a wide range of functions that randomly include many element geometries, multiband reflectors, and frequency windows. Based on these factors, AFSS has evolved in various designs. A short discussion based on these designs of AFSS is discussed in Fig. 3.

2.5D miniaturized multifunctional AFSS (2.5D MMAFSSs)

It is constructed via connected metal strips and parallel metallic plates on an FR4 substrate. The unitary element, as reported, may be shrunk to 0.063 λ_0, where λ_0 is the free-space wavelength, using additional lumped components. The compact design makes creating polarization-insensitive EM modes simple yet has remarkable angle reliability. To verify the idea of a compact design for miniaturization, a "2.5 D MMAFSS" working at 1.9 GHz is designed for evaluation. The experimental findings are excellent and consistent with simulated ones, enabling its use as a multifunctional device for telecommunication [13].

A dual-band electrically beam scanning antenna with a slot AFSS

The construction and testing of a transmitter model for 1.5 and 2.45 GHz wavelength range for beam scanning using SAFSS. Each SAFSS screen unit cell has high tuning ranges and dual modes. For constructing a reliable beam scanning for wireless communication with enhanced network security, certain capacitors are utilized in every layer to overlap the resonance. A dual-band antenna is cheap, simple to build, and efficient in concurrently sweeping beams over an entire 360° angular range in two bands [57].

Reconfigurable bi-state interwoven spiral FSSs

Bi-state switching FSSs often utilize semiconductor switches like PIN diodes. Using a control signal, typically dc bias, at a particular wavelength, the surfaces of a strip component may be rendered reflecting or translucent. PIN diodes join neighboring dipoles to create columns connected by biasing wires. The layer can be radiation-transparent if the high-pass spectrum is narrow and adequate [58]. The structure proves to be highly responsive for isolation and large fractional BWs as compared to the passive FSS.

AFSS of squared aperture with a metal plate loading

Figure 4 depicts the setup of a functional AFSS unit cell. The outer metal is envisioned as vertical rods describing inductors over a similar transmission line for a vertically polarized incident wave for an equivalent circuit. Whereas, when used in parallel with the inductor as capacitors, horizontal bars do not produce horizontal inductances on the equi-voltage bars because of their capacitive nature [59]. The metal loading enables the structure to be modeled with better Q, with diodes with better transmission properties at 2.3 GHz. The unit cell is transmissive for OFF state and high isolation for ON state. The miniaturized immersed FSS comprises a series of unit structures, each comprising a lower frequency selection surface and an upper square resistor ring. From 1 to 2 GHz, the design has strong wave transmission performance, with an absorption rate of more than 90% over the whole Ku band. This can also produce a mono station RCS decrease of more than 10 dB over the entire Ku band. When radiated by oblique incident waves,

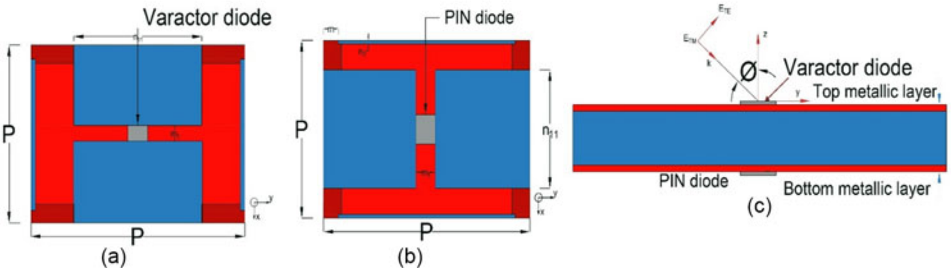

Figure 5. Model of the suggested AFSS unit cell: (a) top view, (b) side view, and (c) cross-sectional view.

this model has the feature of removing grating lobes in an absorption band due to its tiny construction. It can achieve wide-angle and broadband antenna RCS reduction by assuring excellent transmission [67].

Dual-functional AFSS with parallel feeding configuration

A structure comprising two orthogonally fixed metallic layers divided by the slim dielectric layer. Various active devices involving PIN diodes and VDs were employed individually at upper and lower metallic layers. Thus, the frequency tuning function for EM and transverse magnetic (TM) waves is accomplished by providing the working states of these active elements, as shown in Figs. 4 and 5 [58–60, 68–73]. The AFSS design possesses dual function with a better tuning range. The structure is capable of tuning and switching.

Magnetically tuned AFSS

The stability of tunable AFSS includes the incidence of EM waves at various angles and studied switching of the frequency bands. Zhang et al. have proposed a technique for determining the tuning and angular stability of reconfigurable FSS. The simulation findings reveal that by altering the external magnetic field to spin the top layer, AFSS is controlled over the broad frequency range of 6.36–8.81 GHz. The developed AFSS maintains strong tuning stability among frequency bands and is stable from 0° to 80° oblique incidence of EM radiation [24, 73]. The incident wave effects on resonance, insertion loss, passband, and stop band have shown better for magnetically tuned AFSS than diodes, atmospheric light, and 3-D mechanically. A system with two metallic layers separated by a thin dielectric layer is created. Three independently controlled frequency tuning, polarization selection, and EM switching are incorporated into the developed structure using varactor and PIN diodes [12]. A unique biasing setup is intended to need parallel bias voltages for two distinct active device types. The structure exhibits multifunctional features due to a selective injection of a liquid metal alloy into fluidic channels. The proposed model operates effectively under different polarization and oblique incidence situations [74–77]. It is suggested to design a periodic array of the microchannels engraved on an opposing side of the elastomeric substrate [49, 50]. The geometry has the novelty of having independent control in reconfigurability among multiple working states. The prototype shows measured results in close resemblance with simulated responses.

Beam-sweeping reconfigurable response AFSS

A design was proposed in which a monopole antenna and six reflecting AFSS screens are used, and semiconductor switches are used to achieve reconfigurable behavior. The working state of the AFSS screens may be configured by applying various biasing voltages to the diode switches; hence, the monopole antenna's beamwidth and radiation direction can be changed. The omnidirectional scanning outcome can be accomplished at the x–y plane with a step of 60° between 1.8 and 2 GHz, with a maximum radiant efficiency of 96%. Furthermore, with recorded gains of 4.58–6.53 dB, the 3 dB beamwidth may be varied from 176° to 120° [78, 79]. FSS unit elements consisting of a "*split ring slot resonator*" with a VD were researched [80–82]. The proposed AFSS has a single controllable device in every unit element, capable of reflecting and transmitting in two operating bands. The resonance frequency is also tuned in one of the bands through a transmission window. To enable the waveguide simulator to differentiate the AFSS, the unit element "active diaphragm" operating at the X-band is devised and constructed. The measured findings reveal transmitting or reflecting tunable response in a lower band with RF between 9 and 9.35 GHz. The tunable FSS is executed by no resonant subwavelength unit cells loaded with VDs, as [83, 84] suggested. The redshifts created by VDs were utilized to offset the deviation under an oblique incident angle. The suggested tunable AFSS was based on a 2-layer structure comprised of the array of wire grids and the array of split square rings loaded with two DVDs. The practical measurement is conducted in a C-band frequency range, demonstrating the method's viability. The experimental findings match the predictions well, showing angular stability at 4.25 GHz.

Beam steering using AFSS

Wu et al. [40] presented a THz antenna having 360° beam steering. The recommended antenna is a THz multidirectional single pole antenna having the hexagonal screen of AFSS. In terahertz, the AFSS unit cell may be switched ON and OFF by altering the "chemical potential" of graphene from 0 to 0.5 eV. As a result, the antenna can perform 360° beam scanning. Furthermore, unlike traditional AFSS with just two states, the suggested AFSS's transmission and reflection coefficients continually change because of the tunable chemical potential and increasing the antenna's radiation gain. Authors in [85–87] presented the dual-band, independent "beam steering THz antenna" made from a broadband multidirectional single-pole source antenna, surrounded by the six hexagonal screens of AFSS with the switchable filtering response in the two bands. AFSS screen can convert among high transmission and total reflection at two frequency ranges separately by changing "chemical potential" from 0 to 0.5 eV. As a result, the THz antenna's radiation beams in two bands can be directed with variable combinations from 360° large-angle scanning to multidirectional radiation. Wang et al. [88] utilized AFSS to design a "beam-steering antenna" of flower type. The proposed concept includes an antenna of a dual-band patch having unipolar radiation properties, two tunable AFSS layers, and six metallic sheets clustered around EM waves. The AFSS layers determine the broadcast parameters of the indicated antenna. The source's omnidirectional radiation pattern is converted to a multi-beam-directed radiation pattern that operates at 2.45 and 5.8 GHz using different combinations of PIN diodes.

Beam switching using AFSS

Houssein et al. [78] suggested that the ASFSS are utilized to produce a dual-band beam-switching antenna. The dual-band monopole antenna as the source of EM waves and ASFSS is used in the suggested design. The ASFSS was utilized to transform the source's omnidirectional radiation pattern into a directional one, resulting in a reversible antenna. At 2.45 and 5.8 GHz, beam steering with a 90° angular beamwidth was attained using various PIN-diode combinations. References [26, 89–92] used the phase compensation procedure to analyze it and validated using cylindrical FSS and the beam-switching antenna. An omnidirectional dipole and a phase-adjustable AFSS structure were embedded with varactors and an ordered bias voltage under the supervision of a phased compensation technique to steer and gather the dipole pattern. At 2.45 GHz, the suggested antenna achieves the high gain of 13.3 dBi, while fulfilling beam switching with the 20° step. The constructed prototype's measured findings are in good agreement with a simulated one [93–95]. Bouslama et al. [96] proposed the shifting-beam developing superstrate antenna concept. The antenna is made up of two parts: the source patch antenna and the AFSS. The antenna's beam switching was accomplished via PIN diodes. At the 5G frequency, the ON and OFF states of the AFSS show transmission and reflection properties, respectively. When all the diodes are ON, AFSS becomes transparent, and when all the diodes are OFF, AFSS becomes opaque. This unusual occurrence causes the patch's primary beam to shift from broadside to end, firing in an elevation plane. The design can be used in 5G applications [97].

Beam forming using AFSS

References [22, 82, 97–99] suggested AFSS was used to create a unique switched-beamforming antenna. The antenna is made up of two components: an omnidirectional source and a new active triangular frequency selective surface (ATFSS) that surrounds the source. In the ATFSS construction, each unit cell has two diamond-shaped patches linked by the high-frequency PIN diode. The ON and OFF states of ATFSS display transmission and reflection properties in an operational WLAN band by altering the applied biasing voltage. Beam switching at numerous azimuthal directions is done by assembling AFSS unit cells in the triangle configuration with three panels and selecting different combinations of diode states. The suggested antenna is manufactured and measured to validate the concept. At 5.8 GHz, the model and experiment had a high agreement regarding beam directions, reflection coefficient, and gain. Using a Genetic Algorithm software and a 32-element high gain beamforming antenna, authors in [100–103] developed a real-time voltage control framework. The antenna's gain had increased to 8.95 dBi, while the antenna's beamwidth had shrunk to 30°. Sanz-Izquierdo et al. [104] viewed a dual-functional radar-communication (DFRC) method as the favorable component in a developing platform. When integrating the required transmit beam pattern, the degree of freedom of the waveform design is restricted, creating high multi-user interference (MUI) and reducing communication performance. The author also investigated joint waveform passive and designed beamforming in the RIS-assisted DFRC system. Minimizing the MUI under strict beam pattern constraints by mutually optimizing the RIS phase shift matrix and DFRC waveform is studied.

Principle working of AFSS

Active devices are mounted onto passive frequency selective surfaces (PFSS) to affect an AFSS. In contrast to passive FSS, active FSS compensates for its flaws and has a promising future in radar radomes and multifrequency system domains. The electrically operated AFSS is the commonly seen active FSS because of its straightforward design and low cost. In addition to an orthogonal structure of the bottom and top metal layers, which ensures polarization stability, compact unit cells also provide angular stability to the AFSS. According to the simulation outcome, the AFSSs can be used in radar random and unmanned aerial vehicle (UAV) systems [105, 106]. To have a better overall frequency response, the traditional FSSs must be tuned and modified in terms of their frequency response. It is possible to allow or stop a specific frequency by building active FSSs [107–109]. The advantages of such structures are their ease of design and production, but the downside is that they need to be reconfigurable. Active FSSs' EM properties are determined during the design phase, and the only method to modify them is to redesign and rebuild the structure [96, 104].

ElMahgoub et al. [98] defined active FSSs as FSSs having adaptive EM properties. Adaptive approaches introduce dynamic qualities and allow them to be controlled in near-real-time. Furthermore, compared to a passive FSS, an active FSS is substantially smaller. Therefore, incorporating active components within conducting aperture/patch geometries may boost the design's usefulness and reconfigurability, which is crucial for many practical applications [110, 111]. For example, an active FSS would prevent mobile phone signals from entering security areas, such as airport lounges, but other radio, TV, and wireless signals would undoubtedly get through without an issue. However, the complexity of such structure design and production is simply a side of concern [112–114].

To have larger BW, EM structures have been extensively documented based on AFSS for microwave absorption, radomes, and antenna applications [115–122]. Metal-backed microwave absorption models comprised of magnetic materials and dielectric materials generally have a restricted BW. It is also widely known that raising the thickness of coated layers for signal absorbers can enhance absorption BW [123–127]. However, a significant thickness-BW tradeoff restricts the application of such EM structures. Compared to standard FSSs, AFSS's complex structures result in a broader BW and reduced coating thickness [109, 128–131]. A better design component of innovative EM structures is a continuous or discrete tuning of the reflection null in real-time across the large frequency spectrum. Any EM structure's frequency response can be switched from transmitting to reflecting using active FSSs [27, 30, 132, 133]. To create innovative, intelligent EM constructions, such modifying capabilities of a structure are necessary. Previously, such control was achieved using a composite structure with several dielectrics magnetic and conductive elements. Active components can be used to flip among reflection modes and transmission at specific frequencies [134–137]. Table 1 lists EM structures based on AFSS and associated active switching components in the microwave frequency range; Schottky, PIN, MEMS switches, and varactor are frequently utilized switching

Table 1. An overview of reconfigurable FSS based on switching elements and frequency

Switching element employed	Frequency range (GHz)	Authors
Galinstan	7–13	[17, 20]
PIN diode	1–3	[131]
Resistors and capacitors	4–18	[118]
Folding geometry	8–12	[92]
Liquid metal droplets	5–14	[19]
Spring resonator element	3–4	[117]
Schottky diode	1–8	[126]
MEMS bridge	8.2–12.4	[138]
PIN diode	7–13	[81]
Varicap	1–6	[91]

components for active FSS-based EM devices. Many reconfigurable FSSs are developed and extensively researched for several applications for telecommunications, medical devices, and radars. According to the University of Sheffield researchers, the adaptive properties of active FSSs may be acquired by altering a reflection null generated utilizing a flexible impedance structure.

Simulation and optimization approaches

Inductance and capacitance have been shown to impact the absorber's thickness significantly. Purely inductive screens can enhance absorber thickness, whereas purely capacitive screens can decrease absorber thickness. Table 2 shows a variety of distinct approaches, along with their transmission coefficients, reflection coefficients, and beam scanning angles. The Active FSS proposed for the sub-6 GHz, where different switching approaches are designed based on the antenna. The bean scanning is achieved in the range of 10° to 90° which is governed by the topology used in designing the AFSS. The transmission and reflection coefficients, as tabulated in Table 2, emphasize the structure's reliability for the sub-6 GHz BW. These structures, as proposed, illustrate that the operating frequency and FSS architecture significantly impact active FSS-based EM structures' beam scanning angle, transmission coefficient, and reflection coefficient. The complexity of the structure and active element used in AFSS-based structures are critical factors for determining the conformal beam scanning angle achieved. The monopole antenna can be switched to a dual-band with various beam scanning as detailed.

Table 3 shows a schematic analysis of several antennas built and integrated into various FSS, the materials used for multiple operating frequencies, their gain, and beam steering coverage. In context with present-day warfare and communication systems, the need for conformal FSS is being experienced. These types of structures are adaptive to the shape of the platform on which they are mounted. The curvature of the conformal or conical FSS affects the frequency response. The AFSS with the operating frequency and structure complexity having the bean steering capabilities along with switching is tabulated in Table 3. Table 3 lists the designed AFSS structures based on different approaches and components to meet the requirement of beam steering and beam switching. Authors have used ST, ADS, and HFSS methods for examining a wide range of antennas based on operating frequency, gain, and FSS structure.

AFSSs' possible limitations and possible uses in the future

For a very long time, antenna randoms, polarizers, radar absorption materials, reflectors, and composite metamaterials have all been employed with AFSSs. Even though this field of study is relatively new, it has a long history of application and theoretical development due to the abundance of well-developed design and analytic tools. However, significant theoretical and practical issues remain, such as creating non-periodic AFSS and doubly curved AFSS. An AFSS must have a wider BW, crisp band edges, stability, and quicker roll-off with the modification of entering EM wave polarizations and angles. The nature of the array element, its shape, inter-element spacing, dielectric, and structural profiles are characteristics that defined the structure of an AFSS from prior work and this review study. Many essential issues must be addressed in the design of AFSS structures. The selection of a suitable AFSS element, the unit cell's size, the substrate's profile, and the iterations of the layer are all critical. This is to meet the demands of compact and demanding applications. These characteristics have proven

Table 2. Transmission and reflection coefficient overview of different approaches

Author	Beam scanning angle	Approach	Operating frequency	Transmission coefficient	Reflection coefficient
[17]	60°	Dual-band omnidirectional monopole antenna	2.45 GHz	−31.5 dB	−25 dB
[18]	60°	Dual-band omnidirectional monopole antenna	5.2 GHz	−31 dB	−40 dB
[40]	60°	Hybrid graphene-gold structure	1.44 THz	−1.89 dB	−10.6 dB
[89, 110]	60°	Single dipole placed at the center of an active cylindrical FSS	2.4 GHz, 2.8 GHz	−11 dB, −9 dB	−1 dB, −2.25 dB
[139]	30°	Simultaneously achieve filtering and beam steering function	5.3 GHz	−13.65 dB	−6.5 dB
[52–55]	90°	Electronically beam-switching	2.5 GHz	−20 dB	−13 dB
[106]	10°	Capacitive and inductive structures	12 GHz	–	–
[102]	60°	Active cylindrical FSS structure containing PIN diodes	1.8 GHz	–	−32 dB

Table 3. Various AFSS designs in different frequency bands for antenna integration

Reference	Objective	FSS	Operating frequency	Beam steering/switching
[86]	Harmonic suppression	Asymmetric FSS unit cell	2.12 GHz	No
[13]	2.5-D miniaturized multifunctional active frequency-selective surfaces (2.5-D MMAFSSs)	Four independent operating using PIN diodes	1.9 GHz	No
[22–25]	High power protection & switching	Energy selective surface (ESS) with PIN diodes	L-band	No
[135]	Reconfigurable PRS	Half ring FSS	5.5 GHz	Yes
[102]	Switchable absorber/reflector	I Shaped FSS with centrally loaded PIN diodes	S-band	No
[58]	Electromagnetic waves in microware using water	Fluidically programmable metasurfaces (FPMS)	2.57–2.64 GHz	Yes
[16]	Reconfigurable antenna	Artificial dielectric medium (ADM)	5.2 GHz	Yes
[136]	Reconfigurable antenna	Dipole and a cylindrical FSS	2.54 GHz	Yes
[8]	Beam switching	Active decagon prismatic	2.3–2.45 GHz	Yes
[40]	Reconfigurable antenna	Hybrid graphene-gold structure	1.38–1.56	Yes
[93–95]	3-D Beam Scanning	Novel planar feed array and a cylindrical active frequency-selective surface	2.54 GHz	Yes
[89, 110]	Switching antenna	Cylindrical FSS with metallic strips	1.7–1.9 GHz	Yes
[90]	Beamforming antenna	Cylindrical smart dome	2.0–2.70 GHz	Yes
[76]	Reconfigurable FSS	Slot arrays with varactors	4.6–16 GHz	Yes
[97]	Beam sweeping	Dipole with cylindrical FSS	1.8 GHz	Yes

challenging to control and need critical and excellent EM behavior analysis of an AFSS to achieve. Trans-receiver and transgender radar absorption materials, polarizers, composite metamaterials, and reflectors are all examples where AFSSs have been utilized. To build effective FSS structures. Many essential issues must be overcome. Several difficult areas in substantial FSS investigation and practical application where they may have a significant effect on future trends are as follows:

- Vast numbers of unit cells are typically required for a collection to communicate with an incident beam efficiently.
- The difficulty in controlling surface conductivity is also one of the significant problems.
- The capability to protect 5G cellular devices operating at 28 GHz with geometric and polarization consistency is essential.
- The FSS designers need help achieving all the features mentioned above in an optimal design.
- To enhance resonant lengths to meet the issue of reducing the unit cell.
- When creating curved surfaces, increasing the distance between elements and the size of individual components may be troublesome.
- Because of its operational BW limitations, single-layer FSS BW performance is incredibly challenging to enhance.
- When developing new AFSS designs and theories, improving the BW of single-layer AFSS structures is essential.
- AFSS apertures must be as small as feasible to provide better thermal insulation, a significant problem.
- The creation of a doubly curved AFSS, a non-periodic AFSS, is one example of a significant theoretical and practical issue yet to be addressed.

As an alternative to traditional FSS, AFSSs may dynamically tune their EM response by external excitations, which solves the issue of persistent component characteristics in the performance of the former. Many AFSS-related difficulties need the attention of designers in this field. FSS reliability may be degraded from time to time due to interference of the signals caused by a sizeable biasing network. Adding to the complexity and expense of such structures are the manufacturing difficulties. Active FSS's large number of active devices has been a critical source of power consumption issues. A HIS may significantly decrease the number of active components, resulting in a more complicated system. Several more areas of AFSS research and practical applications that might have a significant influence on future trends are discussed in this study.

Designing a realistic AFSS

It is necessary to use thin outer layers with subwavelength thicknesses and low dielectric constant substrates to maintain a continuous BW despite changes in incidence. Even if such materials with low dielectric constants exist, they are not readily accessible now, and they may not be mechanically compatible. An option would be to design such complex elements or develop another solution to this problem [140].

Optimization dilemma

So far, there have been many ways to improve shown or proposed. These, on the other hand, must be used at the proper time and in the right location [141]. Although numerous test cases are required to solve the different incidence polarization and angles, specific designs become problematic or impossible to enhance by calculations. Thus, computer speed and a well-written application would be crucial. Unfortunately, this results in the worst experience for new designers in the real world. For example, the BW and resonance frequency of specific AFSS designs vary widely, and even minor modifications in incidence angles and polarizations may not be effective [122]. Without a viable answer, the computer program may continue to simulate indefinitely. Moreover, many designers are unaware of the need to examine the "dielectric profile" and instead concentrate on adjusting other geometric factors without recognizing the influence on the resonating frequency's instability, cross-polarization, and grating lobes. Designing parameters that consider both the desired and undesirable outcomes is thus a time-consuming and challenging task for anybody involved in its implementation [103].

Design tools

Another problem has to do with the available design tools. "Full-wave analysis" approaches for AFSS geometries are increasingly prevalent, and keeping track of all the developed methods has become challenging. Several commercial software packages provide precise analysis with more excellent dependability. On the other hand, irregular surfaces can be investigated most effectively using such analytical tools since the structure symbolizes the unit element having "subwavelength dimensions." Due to these limitations, additional forms are complicated or uneven. The analysis excludes AFSS geometries such as curved surfaces, closely bound multiple AFSS, and non-periodicity structures. Furthermore, applying "approximation rules" to geometries generally used for a unit element is not feasible because the approximation rules are not applicable [69].

Accurate analysis

Much of the time, a well-estimated AFSS analysis produces a highly accurate, dependable result; as promised to some people's surprise, this only sometimes works in specific designs. Due to the assumption that the current distribution on "array elements" stays constant and that only the phase and amplitude of current fluctuate having incidence angle, the rationale for this is that in certain situations, "odd-modes" may cause the current oblique incidence angle distribution to shift, resulting in the BW no longer being constant, and so failing the analytical test. The difficulty is addressed using compact array components that only retain the principal current distribution inside this resonant zone. However, there is a limit to how small the elements can be and how far they are separated from one another, which may affect how flat the transmission curve's top is. It is thus necessary to choose between continuous BW and a flat top of the frequency response at specific frequencies [125].

Miniaturized design

Because of the need for flexibility in specific applications, miniaturized AFSS, particularly in antenna randoms, are sometimes necessary. Furthermore, substantial element diameters and inter-element spacing were inappropriate for creating curved surfaces. A smaller unit cell size is an attractive option with relatively lower "electrical dimensions" and improved "angular stability" of the AFSSs. The notion of a tiny "array element" has become popular because they distinguish between the operational bands and the grating lobes. Multiple element forms have applied various AFSS downsizing strategies in recent years; nonetheless, this difficulty still needs to be resolved for "much low space" and "stiff" applications, as well as for many other applications [85, 142].

The problem of transmission losses

AFSS, such as radomes, are planned to have minimum transmission losses; nevertheless, they reveal significant losses when tested in real-world circumstances. Even though basic theoretical research implies that these losses account for just a portion of the total, such deficits have significance at a "low-loss substrate." There are several causes of such losses, including dielectric heating, radiation, and Ohmic losses, and it is not easy to distinguish between them all [132, 139].

Fabrication challenges in 3D structures

Compared with traditional AFSS, which are made up of 2D "periodic array elements" that exhibit slow roll-offs, instability, and poor frequency selectivity under various "incident angles," recently reported 3D-AFSS are alleviated, and innovative problems associated with 2D AFSS, as previously reported 3D-AFSS. Although these 3D structures have shown acceptable frequency range response, the complexity is the fundamental problem associated with this sophisticated technology of their development and production. An exhaustive investigation has been conducted to overcome this obstacle. As a result, higher performance and innovative implementations in 3D AFSS as projected to be available just around the corner with a bigger BW, a more comprehensive out-of-band rejection range than currently provided, and in-band steady response [133, 143].

Transmission through energy-saving glass

Energy-saving window glass in today's structures requires a passband AFSS to fulfill several crucial features, the most significant of which are steady frequency response and a good rise in BW. However, FSS apertures must be as tiny as feasible to increase thermal insulation, which presents a significant difficulty [121]. Therefore, a precise etching of the FSS coating is required to prevent the loss of thermal insulation while maintaining the window glass's elegant appearance. Since oxide is present in the coated layer, it is not easy to achieve high resonating FSS and flawless transmission response; nevertheless, recent studies have demonstrated enhanced performance due to meticulous design [70].

Higher operating bandwidth

While designing AFSSs, restricted operational BW is one of the most difficult challenges. As a result, increasing the BW for single-layer AFSS structures is critical. However, although fractal and loop components have been employed to reduce the size of the unit element of the AFSS, it needs to be clarified if this has improved BW. Even though multilayer construction aids in achieving an optimum design, performing more excellent BW, particularly at low operational frequencies, is the most challenging problem for designers [103].

AFSS for intelligent cities applications

Most wireless mobile communication occurs in 6 GHz and lower frequency bands. The Wi-Fi spectrum has significant problems in densely populated areas like conference centers and condominium complexes. Access to more than 24 GHz millimeter-wave frequencies is also required for innovative city applications. EM wave propagation through objects and construction materials is weak in this higher frequency region, causing practical difficulties. To improve RF signals' absorption and conveyance in interior and exterior contexts, FSS systems are placed, as well as inside the buildings. However, to successfully work in these low and higher frequency bands, intelligent city apps must be able to manage the propagation and interference concerns that may arise [127].

AFSS's future developments

Much advancement has been made in the field of AFSS. Table 4 summarizes some of the possible use of AFSS designed for diverse application area, although they are not the only ones, and researchers are also developing new application scenarios [116].

Table 4. Various application areas and utility of AFSS

Applications	Application Area
• Multifunctional AFSS	• Multiband systems, electromagnetic architecture of buildings
• Doubly curbed AFSS surfaces	• Spatial filter applications
• AFSS antenna system integrated design	• Beam switching, beam steering
• AFSS for selective frequency shielding in critical areas such as military systems and airfields	• Stealth technology, shielding
• Dynamically reconfigurable AFSS	• Radiation pattern
• All-dielectric AFSS printed in 3D with a wide bandwidth. • Plasma shells for aerodynamics and protection of terrestrial EM systems are used in the switchable AFSS	• Device manufacturing techniques
• Smart absorbers AFSS • High-performance tunable AFSS Absorber	• EMC & Radar absorption material
• Metamaterial inspired AFSS for Satellite communication • AFSS for earth observation remote sensing and satellites	• Satellite applications
• Chipless passive structural strength monitoring wireless sensor based on AFSS	• Structural health monitoring for hazardous conditions
• Mechanically tunable AFSS	• EM modulation applications
• Graphene-based AFSS	• Filter design
• AFSS for isolating unwanted and harmful radiation at low microwave frequencies in schools, hospitals, and domestic setups	• Radiation control applications
• Wearable sensing AFSS	• Medical applications

Discussions and conclusion

Active FSS elements using semiconductor devices are used to regulate EM properties. The frequency response of AFSS relies on their periodicity size and makes them easy to manipulate by carefully determining all design factors, such as FSS form, periodicity, and size. This simple design enables the operation of an external control signal to change the characteristics of the semiconductor devices. Semiconductor loading is one of the most effective approaches for introducing dynamic frequency response. It is through proper bias voltage across a series of bias lines. The element's shape usually determines the number of bias lines. Compared to ferrite-controlled devices, another essential attribute of semiconductors is their compact size, cost-effectiveness, and quick speed. The diode's greater capacitance dominates an AFSS comprised of an array of dipoles loaded with semiconductor diodes. It can result in a virtual rise in dipole length that can downward the resonance frequency.

This overview offers a valuable viewpoint on one of the fastest-growing areas of current EM and inquiry of an essential "periodic structure" known as AFSS and its kinds and functions. Various studies on AFSS structures have been given till now, considering contemporary emerging trends in communication. From the most basic AFSS to the most complex, from the convoluted/meandered to the most sophisticated and, numerous categories are grouped in this category. Basic 2D AFSS with low mass weight and volume has been employed in several applications, and advanced 3D active FSS with better efficiency can compensate for the manufacturing complexity. When comparing various design techniques, array element topologies, frequency and BW ranges, and polarizability, much data are provided in tables.

The AFSS development fraternity and a broad spectrum of microwave investigators might benefit from this work by comparing and developing new methods. An AFSS architecture may be helpful for many prospective and realistic applications in diverse frequency ranges comprising microwave, millimeter-wave (MW), terahertz (THz), and optical. To give a brief idea of the breadth and depth of AFSS's technical expertise, see Table 5. Since AFSS design, existing or innovative implementation, and manufacturing processes are studied further. It means that novel AFSSs will be a viable option for traditional, underperforming FSSs in the future. This analysis will assist in connecting the theoretical basis with structural dimensions and performance characteristics in cutting-edge AFSS designs.

Our research includes several things that could be improved, including missing data, possible biases, and misclassification. Further, despite conducting thorough research across many domains, relevant publications may have included all the publications addressing the design of AFSS. This circumstance may have the unintended effect of injecting bias into the data we attempted to gather. In this review paper, the element used in AFSS, structural profile, beam switching, beam scanning/steering capabilities, and approaches have been discussed in detail. From the structural perspective, researchers have used various topologies to achieve the intended goal. Since it is imperative to add the active elements and the biasing line to the AFSS-based structures, the topology must be as simple as possible, like a simple ring, loop, or their derivatives. The biasing lines should be designed with a minimum metallic footprint on the substrate to avoid its intervention in the functioning of the structure. Otherwise, the biasing arrangement should be made a part of the AFSS structure.

Further, with the advancement of technology, many attractive fabrication solutions are also available, and among them, additive manufacturing is gaining momentum for the passive structure and should also be explored for the AFSS design to improve the modal accuracy. The paper also discusses the possible limitations and future applications of AFSS and presents a detailed study of AFSS

Table 5. Practical applications of AFSS

AFSS reference	Application	AFSS reference	Application
[119, 129]	Lens/optics	[26]	Mobile communication
[18]	Wireless charging	[69, 70, 84, 98]	X band AFSS, C band AFSS
[41]	Textile AFSS	[22]	5 G EMI reduction AFSS
[74]	Optical AFSS	[72, 124]	EM shielding, medical applications
[72]	Wearable AFSS	[104]	Radio astronomy
[130, 134]	AFSS absorber	[22, 112]	Terahertz band
[115]	RFID	[114, 116]	6G network
[98]	AFSS antenna	[140, 144]	EMI shielding, medical
[113, 138]	Wireless power transmission	[61]	Actuators

used for various applications. Certain new areas of applications, like smart homes, wireless power transmission, health monitoring systems, etc., have been identified in Tables 4 and 5, which may serve as the future direction of the research in the field of AFSS design, analysis, and integration.

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References

1. **Munk BA** (2000) *Frequency Selective Surfaces: Theory and Design*. New York: John Wiley & Sons.
2. **Yan M, Qu S, Wang J, Zhang J, Zhou H, Chen H and Zheng L** (2014) A miniaturized dual-band FSS with stable resonance frequencies of 2.4 GHz/5 GHz for WLAN applications. *IEEE Antennas and Wireless Propagation Letters* **13**, 895–898.
3. **Yan M, Qu S, Wang J, Zhang J, Zhang A, Xia S and Wang W** (2014) A novel miniaturized frequency selective surface with stable resonance. *IEEE Antennas and Wireless Propagation Letters* **13**, 639–641.
4. **Jha KR, Jibran ZAP and Sharma SK** (2022) Absorption peak controlled low-frequency wideband flexible FSS Absorber. *IEEE Transactions on Electromagnetic Compatibility* **64**(4), 975–986.
5. **Jha KR, Mishra G and Sharma SK** (2018) Design of a compact microwave absorber using parameter retrieval method for wireless communication applications. *IET Microwaves, Antennas and Propagation* **12**(6), 977–985.
6. **Campbell SD and Ziolkowski RW** (2012) Lightweight, flexible, polarization-insensitive, highly absorbing meta-films. *IEEE Transactions on Antennas and Propagation* **61**(3), 1191–1200.
7. **Song K and Mazumder P** (2013) Design of highly selective metamaterials for sensing platforms. *IEEE Sensors Journal* **13**(9), 3377–3385.
8. **Yu J, Jiang W and Gong S** (2018) Triple-band beam switching antenna based on active frequency selection surfaces. In *International Symposium on Antennas and Propagation (ISAP), 2018*. IEEE Publications, 1–2.
9. **Shi Y, Tang W, Zhuang W and Wang C** (2014) Miniaturized frequency selective surface based on a 2.5-dimensional closed loop. *Electronics Letters* **50**(23), 1656–1658.
10. **Liang J, Cao Q, Wang Y and Wan Z** (2021) A multifunctional and miniaturized flexible active frequency selective surface. *IEEE Antennas and Wireless Propagation Letters* **20**(12), 2549–2553.
11. **Li B and Shen Z** (2013) Three-dimensional dual-polarized frequency selective structure with wide out-of-band rejection. *IEEE Transactions on Antennas and Propagation* **62**(1), 130–137.
12. **Li H, Ma C, Zhou T, Wang J, Ye D, Sun Y, Zhu W, Denidni TA and Ran L** (2019) Reconfigurable Fresnel lens based on an active second-order bandpass frequency-selective surface. *IEEE Transactions on Antennas and Propagation* **68**(5), 4054–4059.
13. **Li H, Costa F, Fang J, Liu L, Wang Y, Cao Q and Monorchio A** (2019) 2.5-D miniaturized multifunctional active frequency-selective surface. *IEEE Transactions on Antennas and Propagation* **67**(7), 4659–4667.
14. **Li H, Costa F, Fang J, Wang Y, Cao Q and Monorchio A** (2018) Dual-functional active frequency selective surface using parallel feeding configuration and its equivalent circuit model. *International Journal of RF and Microwave Computer-Aided Engineering* **28**(7), e21450.
15. **Li H, Cao Q, Liu L and Wang Y** (2018) An improved multifunctional active frequency selective surface. *IEEE Transactions on Antennas and Propagation* **66**(4), 1854–1862.
16. **Li J, Zeng Q and Denidni TA** (2018) Pattern reconfigurable antenna loaded with frequency selective surface and artificial dielectric medium. In *IEEE International Symposium on Antennas and Propagation and USNC/URSI National Radio Science Meeting, 2018*. IEEE Publications, 975–976.
17. **Li J, Zeng Q, Liu R and Denidni TA** (2017) A compact dual-band beam-sweeping antenna based on active frequency selective surfaces. *IEEE Transactions on Antennas and Propagation* **65**(4), 1542–1549.
18. **Li L, Zhang P, Cheng F, Chang M and Cui TJ** (2021) An optically transparent near field focusing metasurface. *IEEE Transactions on Microwave Theory and Techniques* **69**(4), 2015–2027.
19. **Li M and Behdad N** (2012) Fluidically tunable frequency selective/phase shifting surfaces for high-power microwave applications. *IEEE Transactions on Antennas and Propagation* **60**(6), 2748–2759.
20. **Li M, Yu B and Behdad N** (2010) Liquid-tunable frequency selective surfaces. *IEEE Microwave and Wireless Components Letters* **20**(8), 423–425.
21. **Zhang L, Yang G, Wu Q and Hua J** (2012) A novel active frequency selective surface with a wideband tuning range for EMC purposes. *IEEE Transactions on Magnetics* **48**(11), 4534–4537.
22. **Zhang L, Wu Q and Denidni TA** (2013) Electronically radiation pattern steerable antennas using active frequency selective surfaces. *IEEE Transactions on Antennas and Propagation* **61**(12), 6000–6007.
23. **Zhang J, Lin M, Wu Z, Ding L, Bian L and Liu P** (2019) Energy selective surface with power-dependent transmission coefficient for high-power microwave protection in waveguide. *IEEE Transactions on Antennas and Propagation* **67**(4), 2494–2502.
24. **Zhang CR, Yang Y and He XX** (2020). A magnetically tuned AFSS with good stability and the design method of characteristic parameters. In *Cross-strait radio science & wireless technology conference (CSRSWTC), 2020*. IEEE Publications, 1–3.
25. **Zhang JW, Ke JC and Liang JC** (2021) A dual-band active frequency selective surface with switchable transmission and reflection. In *2021 IEEE 4th International Conference on Electronic Information and Communication Technology (ICEICT)*. IEEE Publications, 830–832.
26. **Zhang LM, Ding X and Shao W** (2021) A phase compensation beam switching antenna based on frequency selective surface. *IEEE Antennas and Wireless Propagation Letters* **20**(9), 1741–1744.
27. **Zhang XY, Chan CH, Xue Q and Hu BJ** (2011) RF tunable bandstop filters with constant bandwidth based on a doublet configuration. *IEEE Transactions on Industrial Electronics* **59**(2), 1257–1265.

28. **Valderrama-Zurián JC, Aguilar-Moya R, Melero-Fuentes D and Aleixandre-Benavent R** (2015) A systematic analysis of duplicate records in Scopus. *Journal of Informetrics* **9**(3), 570–576.
29. **Ford KL, Roberts J, Zhou S, Fong G and Rigelsford J** (2013) Reconfigurable frequency selective surface for use in secure electromagnetic buildings. *Electronics Letters* **49**(14), 861–863.
30. **Anwar RS, Mao L and Ning H** (2018) Frequency selective surfaces: A review. *Applied Sciences* **8**(9), 1689.
31. **Bayatpur F and Sarabandi K** (2010) Design and analysis of a tunable miniaturized-element frequency-selective surface without bias network. *IEEE Transactions on Antennas and Propagation* **58**(4), 1214–1219.
32. **Bayatpur F and Sarabandi K** (2009) A tunable metamaterial frequency-selective surface with variable modes of operation. *IEEE Transactions on Microwave Theory and Techniques* **57**(6), 1433–1438.
33. **Nauman M, Saleem R, Rashid AK and Shafique MF** (2016) A miniaturized flexible frequency selective surface for X-band applications. *IEEE Transactions on Electromagnetic Compatibility* **58**(2), 419–428.
34. **Panwar R and Lee JR** (2017) Progress in frequency selective surface-based smart electromagnetic structures: A critical review. *Aerospace Science and Technology* **66**, 216–234.
35. **Panwar R, Puthucheri S, Agarwala V and Singh D** (2015) Fractal frequency selective surface embedded broadband microwave absorber using disassembled waste printed circuit boards. In *National Conference on Recent Advances in Electronics y Computer Engineering (RAECE), 2015*. IEEE Publications, 116–119.
36. **Rashid AK, Li B and Shen Z** (2014) An overview of three-dimensional frequency-selective structures. *IEEE Antennas and Propagation Magazine* **56**(3), 43–67.
37. **Thakur S, Yadava RL and Das S** (2013) A review on Adaptive Frequency Selective Surfaces (AFSS) based patch antennas. In *Computing, communications, and IT applications conference (ComComAp), 2013*. IEEE Publications, 120–124.
38. **Al-Atrakchii M, Sayidmarie K and Abd-Alhameed R** (2020) Frequency selective surface using the metamaterial property of the U-shaped strip.
39. **Aguilar NN, Boccato L, Junqueira CC and Weber MW**. (2019). A multiobjective perspective for the design of frequency selective surfaces.
40. **Wu B, Hu Y, Zhao YT, Lu WB and Zhang W** (2018) Large angle beam steering THz antenna using active frequency selective surface based on hybrid graphene-gold structure. *Optics Express* **26**(12), 15353–15361.
41. **Chiu CN and Chang KP** (2009) A novel miniaturized-element frequency selective surface having a stable resonance. *IEEE Antennas and Wireless Propagation Letters* **8**, 1175–1177.
42. **Thirumal Murugan J, Suresh Kumar TR, Salil P and Venkatesh C** (2015) Dual frequency selective transparent front doors for microwave oven with different opening areas. *Progress in Electromagnetics Research Letters* **52**, 11–16.
43. **Liang B, Sanz-Izquierdo B, Parker EA and Batchelor JC** (2014) Cylindrical slot FSS configuration for beam-switching applications. *IEEE Transactions on Antennas and Propagation* **63**(1), 166–173.
44. **Mohri M and Rostamizadeh A** (2013) *Perceptron mistake bounds. arXiv preprint arXiv:1305.0208.*
45. **Xue JY, Gong SX, Zang PF, Wang W and Zhang FF** (2010) A new miniaturized fractal frequency selective surface with excellent angular stability. *Progress In Electromagnetics Research Letters* **13**, 131–138.
46. **Wang X, Fei Z, Zheng Z and Guo J** (2021) Joint waveform design and passive beamforming for RIS-assisted dual-functional radar-communication system. *IEEE Transactions on Vehicular Technology* **70**(5), 5131–5136.
47. **Sohail SI** (2016). Wi-Fi transmission and multiband shielding using single-layer frequency selective surface. In *IEEE International Symposium on Antennas and Propagation (APSURSI), 2016*. IEEE Publications, 963–964.
48. **Ghosh S and Srivastava KV** (2016) Polarization-insensitive single-and broadband switchable absorber/reflector and its realization using a novel biasing technique. *IEEE Transactions on Antennas and Propagation* **64**(8), 3665–3670.
49. **Ghosh S, Phon R, Tentzeris MM and Lim S** (2018) An improved multi-functional frequency selective surface based on microfluidic technology. In *International Symposium on Antennas and Propagation (ISAP), 2018*. IEEE Publications, 1–2.
50. **Suryadinata AS and Pranjoto H** (2018) Equalizer digital dengan pengontrol menggunakan komputer. *Widya Teknik* **13**(2), 14–22.
51. **Sanz-Izquierdo B, Parker EA, Robertson J-B and Batchelor JC** (2010) Tuning patch-form FSS. *Electronics Letters* **46**(5), 329–330.
52. **Sanz-Izquierdo B, Parker EA, Robertson J-B and Batchelor JC** (2009) Tuning technique for active FSS arrays. *Electronics Letters* **45**(22), 1107–1109.
53. **Sanz-Izquierdo B, Parker EA and Batchelor JC** (2011) Switchable frequency selective slot arrays. *IEEE Transactions on Antennas and Propagation* **59**(7), 2728–2731.
54. **Sanz-Izquierdo B and Parker EA** (2013) 3D printing technique for fabrication of frequency selective structures for built environment. *Electronics Letters* **49**(18), 1117–1118.
55. **Sivasamy R, Murugasamy L, Kanagasabai M, Sundarsingh EF and Gulam Nabi Alsath MGN** (2016) A low-profile paper substrate-based dual-band FSS for GSM shielding. *IEEE Transactions on Electromagnetic Compatibility* **58**(2), 611–614.
56. **Zhang Y, Feng Y and Zhao J** (2020) Graphene-enabled active metamaterial for dynamical manipulation of terahertz reflection/transmission/absorption. *Physics Letters A* **384**(33), 126840.
57. **Najafy V and Abbasi Arand BA** (2021) A novel dual-band beam scanning antenna based on slot active frequency-selective surfaces [antenna applications corner]. *IEEE Antennas and Propagation Magazine* **63**(3), 94–143.
58. **Vallecchi A, Langley RJ and Schuchinsky AG** (2014). Active singly and dual polarised interwoven spiral frequency selective surfaces. In *The 8th European Conference on Antennas and Propagation (EuCAP 2014)*. IEEE Publications, 616–619.
59. **Chang K and Yoon YJ** (2008) Active frequency selective surfaces using incorporated PIN diodes. *IEICE Transactions on Electronics* **91**(12), 1917–1922.
60. **Mavridou M, Feresidis AP, Gardner P and Hall PS** (2014) Tunable millimeter-wave phase shifting surfaces using piezoelectric actuators. *IET Microwaves, Antennas and Propagation* **8**(11), 829–834.
61. **Doken B and Kartal M** (2019). An active frequency selective surface design has four different switchable frequency characteristics.
62. **Kasar Ö and Belen MA** (2020) Realization of reconfigurable filtering horn antennas using active frequency selective surfaces for GSM and LTE signal filtering. *International Journal of RF and Microwave Computer-Aided Engineering* **30**(11), e22429.
63. **Yang C, Li H, Cao Q and Wang Y** (2015). Reconfigurable shield by active frequency selective surface for LTE2. 1GHz and WiFi2. In *2015 Asia and the Pacific Microwave Conference (APMC), 1*. IEEE Publications, 45GHz.
64. **Boccia L, Russo I, Amendola G and Di Massa G** (2009) Tunable frequency-selective surfaces for beam-steering applications. *Electronics Letters* **45**(24), 1213–1215.
65. **Kiani GI, Olsson LG, Karlsson A, Esselle KP and Nilsson M** (2010) Cross-dipole bandpass frequency selective surface for energy-saving glass used in buildings. *IEEE Transactions on Antennas and Propagation* **59**(2), 520–525.
66. **Fang X, Cao Q, Zhou Y and Wang Y** (2018) Multiscale compressed block decomposition method with characteristic basis function method and fast adaptive cross approximation. *IEEE Transactions on Electromagnetic Compatibility* **61**(1), 191–199.
67. **Edalati A and McCollough W** (2017) A novel dual-band beam-switching antenna based on active frequency selective surfaces. In *IEEE International Symposium on Antennas and Propagation and USNC/URSI National Radio Science Meeting, 2017*. IEEE Publications, 1985–1986.
68. **Farooq U, Iftikhar A, Shafique MF, Babar Abbasi MAB, Clendinning S, Fida A, Mughal MJ and Khan MS** (2020) Ultraminiaturised polarisation selective surface (PSS) for dual-band Wi-Fi and WLAN shielding applications. *IET Microwaves, Antennas and Propagation* **14**(13), 1514–1521.
69. **Farooq U, Iftikhar A, Shafique MF, Khan MS, Fida A, Mughal MJ and Anagnostou DE** (2021) C-band and X-band switchable frequency-selective surfaces. *Electronics* **10**(4), 476.

70. **Lin S, Zheng B, Alexandropoulos GC, Wen M, Chen F and Mumtaz S** (2020) Adaptive transmission for reconfigurable intelligent surface-assisted OFDM wireless communications. *IEEE Journal on Selected Areas in Communications* **38**(11), 2653–2665.
71. **Liu M** (2020) Four-layer tunable wideband electromagnetic shield based on cold plasma. *IEEE Access* **8**, 171621–171627.
72. **Lu C and Chen X** (2020) Latest advances in flexible symmetric supercapacitors: From material engineering to wearable applications. *Accounts of Chemical Research* **53**(8), 1468–1477.
73. **Ma C, Li H, Zhang B, Ye D, Huangfu J, Sun Y, Zhu W, Li C and Ran L** (2020) Implementation of a 2-D reconfigurable Fresnel-zone-plate antenna. *IEEE Transactions on Antennas and Propagation* **69**(1), 520–525.
74. **Mahmood SM and Denidni TA** (2014, July). Reconfigurable antenna using novel active frequency selective surface. In *IEEE Antennas and Propagation Society International Symposium (APSURSI), 2014*. IEEE Publications, 1236–1237.
75. **Majidzadeh M, Ghobadi C and Nourinia J** (2016) Novel single-layer reconfigurable frequency selective surface with UWB and multiband modes of operation. *AEU – International Journal of Electronics and Communications* **70**(2), 151–161.
76. **Mantash M and Denidni TA** (2019) CP antenna array with switching-beam capability using electromagnetic periodic structures for 5-G applications. *IEEE Access* **7**, 26192–26199.
77. **Hou J, Chen Z, Wang Z, Huang D and Denidni TA** (2021) Beam-sweeping antenna with beamwidth reconfigurable response. *International Journal of RF and Microwave Computer-Aided Engineering* **31**(12), e22877.
78. **Houssein H, Elzwawi G and Denidni TA** (2019) A dual-band beam-switching antenna using square active frequency selective surfaces. In *IEEE International Symposium on Antennas and Propagation and USNC-URSI Radio Science Meeting, 2019*. IEEE Publications, 685–686.
79. **Esparza-Aguilar TE, Rodriguez-Cuevas J, Martynyuk AE and Martinez-Lopez JI** (2020) Active frequency selective surface with tunable and switchable properties based on loaded split ring slots. *Electronics Letters* **56**(7), 319–321.
80. **Fabian-Gongora H, Martynyuk AE, Rodriguez-Cuevas J and Martinez-Lopez JI** (2015) Active dual-band frequency selective surfaces with close band spacing based on switchable ring slots. *IEEE Microwave and Wireless Components Letters* **25**(9), 606–608.
81. **Elzwawi GH, Elzuwawi HH, Tahseen MM and Denidni TA** (2018) Frequency selective surface-based switched-beamforming antenna. *IEEE Access* **6**, 48042–48050.
82. **Bai H, Yan M, Li W, Wang J, Zheng L, Wang H and Qu S** (2021) Tunable frequency selective surface with angular stability. *IEEE Antennas and Wireless Propagation Letters* **20**(6), 1108–1112.
83. **Bay P** (2020). *Active limiting frequency: Selective surface at X-band* ([Doctoral Dissertation]. Colorado School of Mines).
84. **Yang J, Chen J, Quan L, Zhao Z, Shi H and Liu Y** (2021) Metamaterial-inspired optically transparent active dual-band frequency selective surface with independent wideband tunability. *Optics Express* **29**(17), 27542–27553.
85. **Yang X, Luyen H, Xu S and Behdad N** (2019) Design method for low-profile, harmonic-suppressed filter-antennas using miniaturized-element frequency selective surfaces. *IEEE Antennas and Wireless Propagation Letters* **18**(3), 427–431.
86. **Yang YJ, Wu B, Zhao YT and Chi-Fan** (2021) Dual-band beam steering THz antenna using active frequency selective surface based on graphene. *EPJ Applied Metamaterials* **8**, 12.
87. **Elzwawi G and Denidni TA** (2020) A flower-shaped beam-steering antenna for wireless communication Systems. In *IEEE International Symposium on Antennas and Propagation and North American Radio Science Meeting, 2020*. IEEE Publications, 181–182.
88. **Wang Y, Li S, Xiong W and Zhai H** (2019) A miniaturized absorbed frequency selective surface based on a square resistor ring with low radar cross-section. *Microwave and Optical Technology Letters* **61**(11), 2527–2533.
89. **Ding T, Zhang S, Zhang L and Liu Y** (2017) Smart cylindrical dome antenna based on active frequency selective surface. *International Journal of Antennas and Propagation* **2017**, 1–14.
90. **Ferreira D, Cuiñas I, Caldeirinha RFS and Fernandes TR** (2016) Dual-band single-layer quarter ring frequency selective surface for Wi-Fi applications. *IET Microwaves, Antennas and Propagation* **10**(4), 435–441.
91. **Fuchi K, Tang J, Crowgey B, Diaz AR, Rothwell EJ and Ouedraogo RO** (2012) Origami tunable frequency selective surfaces. *IEEE Antennas and Wireless Propagation Letters* **11**, 473–475.
92. **Gu C, Izquierdo BS, Gao S, Batchelor JC, Parker EA, Qin F, Wei G, Li J and Xu J** (2017) Dual-band electronically beam-switched antenna using slot active frequency selective surface. *IEEE Transactions on Antennas and Propagation* **65**(3), 1393–1398.
93. **Gu C, Gao S, Sanz-Izquierdo B, Parker EA, Qin F, Xu H, Batchelor JC, Yang X and Cheng Z** (2017) 3-D coverage beam-scanning antenna using feed array and active frequency-selective surface. *IEEE Transactions on Antennas and Propagation* **65**(11), 5862–5870.
94. **Gu C, Gao S, Sanz-Izquierdo B, Parker EA, Li W, Yang X and Cheng Z** (2017) Frequency-agile beam-switchable antenna. *IEEE Transactions on Antennas and Propagation* **65**(8), 3819–3826.
95. **Shoaib N and Raza A** (2019, December). Beam switching using Active Frequency Selective Surface (AFSS) for 5-G applications. In *Photonics y Electromagnetics Research Symposium, 2019*. IEEE Publications, 2775–2780.
96. **Bouslama M, Traii M, Denidni TA and Gharsallah A** (2015) Beam-switching antenna with a new reconfigurable frequency selective surface. *IEEE Antennas and Wireless Propagation Letters* **15**, 1159–1162.
97. **Abdollahvand M, Forooraghi K, Atlasbaf Z, Martinez-de-rioja E, Encinar JA, Ebrahimi A and Ghosh S** (2021, March). Reconfigurable FSS based on PIN diodes for shared-aperture X/Ka-band antennas. In *15th European Conference on Antennas and Propagation (EuCAP), 2021*. IEEE Publications, 1–4.
98. **ElMahgoub K, Yang F and Elsherbeni AZ** (2013) Design of novel reconfigurable frequency selective surfaces with two control techniques. *Progress in Electromagnetics Research C* **35**, 135–145.
99. **Zhao Y, Zhang L, Xu X, Yu F and Liu Q** (2014) A GA-based real-time voltage platform for a 32-element high gain beam-forming antenna optimization. In *Proceedings of the 2014 3rd Asia-Pacific Conference on Antennas and Propagation*. IEEE Publications, 917–919.
100. **Zhong X, Xu HX, Chen L, Li W, Wang H and Shi X** (2019) An FSS-backed broadband phase-shifting surface array with multimode operation. *IEEE Transactions on Antennas and Propagation* **67**(9), 5974–5981.
101. **Zhao R, Gong B, Xiao F, He C and Zhu W** (2019) Circuit model analysis of switchable perfect absorption/reflection in an active frequency selective surface. *IEEE Access* **7**, 55518–55523.
102. **Zhao B, Huang C, Yang J, Song J, Guan C and Luo X** (2020) Broadband polarization-insensitive tunable absorber using active frequency selective surface. *IEEE Antennas and Wireless Propagation Letters* **19**(6), 982–986.
103. **Wang SH, He XX and Yang Y** (2020) An active tunable frequency selective surface based on the rotatable magnet. In *Cross-Strait Radio Science & Wireless Technology Conference (CSRSWTC), 2020*. IEEE Publications, 1–3.
104. **Sanz-Izquierdo B and Parker EA** (2013) Dual polarized reconfigurable frequency selective surfaces. *IEEE Transactions on Antennas and Propagation* **62**(2), 764–771.
105. **Sazegar M, Zheng Y, Kohler C, Maune H, Nikfalazar M, Binder JR and Jakoby R** (2012) Beam steering transmit array using tunable frequency selective surface with integrated ferroelectric varactors. *IEEE Transactions on Antennas and Propagation* **60**(12), 5690–5699.
106. **Cure D, Weller TM and Miranda FA** (2012) Study of a low-profile 2.4-GHz planar dipole antenna using a high-impedance surface with 1-D varactor tuning. *IEEE Transactions on Antennas and Propagation* **61**(2), 506–515.
107. **Cure D, Weller TM, Miranda FA and Price T** (2013) Low profile tunable dipole antenna using BST varactors for biomedical applications. In *IEEE Antennas and Propagation Society International Symposium (APSURSI), 2013*. IEEE Publications, 570–571.

108. **Cure D, Weller TM, Price T, Miranda FA and Van Keuls FW** (2013) Low-profile tunable dipole antenna using barium strontium titanate varactors. *IEEE Transactions on Antennas and Propagation* **62**(3), 1185–1193.
109. **Edalati A and Denidni TA** (2011) Beam-switching antenna based on active frequency selective surfaces. In *IEEE International Symposium on Antennas and Propagation (APSURSI), 2011*. IEEE Publications, 2254–2257.
110. **Taylor PS, Parker EA and Batchelor JC** (2011) An active annular ring frequency selective surface. *IEEE Transactions on Antennas and Propagation* **59**(9), 3265–3271.
111. **Anusha K, Mohana Geetha D and Amsaveni A** (2021) Overview of THz antenna design methodologies. In Das S, Anveshkumar N, Dutta J and Biswas A, *Advances in Terahertz Technology and Its Applications*. Singapore: Springer, 337–362.
112. **Anand Y, Mittal A and Raheja DK** (2021) Active frequency selective surface for duplexers in wireless applications. In *2nd International Conference for Emerging Technology (INCET), 2021* . IEEE Publications, 1–4.
113. **Alwahishi R, Ali MMM, Elzwaw G and Denidni TA** (2021) Reconfigurable dual-band 28/38-GHz frequency selective surface for 6-G applications. In *19th International Symposium on Antenna Technology and Applied Electromagnetics (ANTEM), 2021*. IEEE Publications, 1–2.
114. **Ahmed H, Nasrazadani S and Ju S** (2021) Review paper on harsh environmental structural health monitoring. *Elastic* **4**, 20.
115. **Alexandropoulos GC, Lerosey G, Debbah M and Fink M** (2020) Reconfigurable intelligent surfaces and metamaterials: The potential of wave propagation control for 6G wireless communications. *arXiv preprint arXiv,* 2006.11136.
116. **Azemi SN, Ghorbani K and Rowe WST** (2013) A reconfigurable FSS using a spring resonator element. *IEEE Antennas and Wireless Propagation Letters* **12**, 781–784.
117. **Chen Q, Jiang JJ, Xu XX, He Y, Chen L, Sun B, Bie SW, Miao L and Zhang L** (2012) Thin and broadband electromagnetic absorber design using resistors and capacitors loaded frequency selective surface. *Journal of Electromagnetic Waves and Applications* **26**(16), 2102–2111.
118. **Cho S and Song HJ** (2020) Ultra-low power beamforming wideband OFDM signal with active GRIN lens at 19 GHz. In *IEEE International Symposium on Antennas and Propagation and North American Radio Science Meeting, 2020*. IEEE Publications, 583–584.
119. **Costa F, Monorchio A and Vastante GP** (2011) Tunable high-impedance surface with a reduced number of varactors. *IEEE Antennas and Wireless Propagation Letters* **10**, 11–13.
120. **Das P, Mandal K and Lalbakhsh A** (2020) Single-layer polarization-insensitive frequency selective surface for beam reconfigurability of monopole antennas. *Journal of Electromagnetic Waves and Applications* **34**(1), 86–102.
121. **Gong S, Lu X, Hoang DT, Niyato D, Shu L, Kim DI and Liang YC** (2020) Toward smart wireless communications via intelligent reflecting surfaces: A contemporary survey. *IEEE Communications Surveys and Tutorials* **22**(4), 2283–2314.
122. **Lazaro A, Ramos A, Girbau D and Villarino R** (2012) A novel UWB RFID tag using active frequency selective surface. *IEEE Transactions on Antennas and Propagation* **61**(3), 1155–1165.
123. **Koohestani M, Perdriau R, Ramdani M and Carlsson J** (2020) Frequency selective surfaces for electromagnetic shielding of pocket-sized transceivers. *IEEE Transactions on Electromagnetic Compatibility* **62**(6), 2785–2792.
124. **Kodama K, Nagai T, Kuwaki A, Jinnouchi R and Morimoto Y** (2021) Challenges in applying highly active Pt-based nanostructured catalysts for oxygen reduction reactions to fuel cell vehicles. *Nature Nanotechnology* **16**(2), 140–147.
125. **Kitagawa S, Suga R, Araki K and Hashimoto O** (2015). Active absorption/transmission FSS using diodes. In *IEEE International Symposium on Electromagnetic Compatibility (EMC)*. IEEE Publications, 1538–1541.
126. **Phon R and Lim S** (2020) Design and analysis of active metamaterial modulated by RF Power Level. *Scientific Reports* **10**, 8703.
127. **Xu W and Sonkusale S** (2013) Microwave diode switchable metamaterial reflector/absorber. *Applied Physics Letters* **103**(3), 031902.
128. **Xi Q, Ma C, Li H, Zhang B, Li C and Ran L** (2020) A reconfigurable planar Fresnel lens for millimeter-wave 5G frontends. *IEEE Transactions on Microwave Theory and Techniques* **68**(11), 4579–4588.
129. **Ye S and Cao Q** (2020) An optically controlled active frequency selection surface for absorption adjustment function. In *Cross-strait radio science & wireless technology conference (CSRSWTC), 2020*. IEEE Publications, 1–3.
130. **Zareian-Jahromi E and Khalilpour J** (2011) Analysis of a freestanding frequency selective surface loaded with a nonlinear element. *Journal of Electromagnetic Waves and Applications* **25**(2–3), 247–255.
131. **Mishra R and Panwar R** (2020) Investigation of graphene fractal frequency selective surface loaded terahertz absorber. *Optical and Quantum Electronics* **52**(6), 1–13.
132. **Kapoor A, Kumar P and Mishra R** (2021) Analysis and design of a passive spatial filter for sub-6 GHz 5-G communication systems. *Journal of Computational Electronics* **20**(5), 1900–1915.
133. **Huang C, Song J, Ji C, Yang J and Luo X** (2020) Simultaneous control of absorbing frequency and amplitude using graphene capacitor and active frequency-selective surface. *IEEE Transactions on Antennas and Propagation* **69**(3), 1793–1798.
134. **Ji LY, Zhang ZY and Liu NW** (2019) A two-dimensional beam-steering partially reflective surface (PRS) antenna using a reconfigurable FSS structure. *IEEE Antennas and Wireless Propagation Letters* **18**(6), 1076–1080.
135. **Han L, Cheng G, Han G, Ma R and Zhang W** (2018) Electronically beam-steering antenna with active frequency-selective surface. *IEEE Antennas and Wireless Propagation Letters* **18**(1), 108–112.
136. **Umair H, Latef TBA, Yamada Y, Hassan T, Mahadi WNLBW, Othman M, Kamardin K and Hussein MI** (2021) Quarter wavelength Fabry–Perot Cavity antenna with wideband low monostatic radar cross section and off-broadside peak radiation. *Applied Sciences* **11**(3), 1053.
137. **He Y, Feng W, Guo S, Wei J, Zhang Y, Huang Z, Li C, Miao L and Jiang J** (2020) Design of a dual-band electromagnetic absorber with frequency-selective surfaces. *IEEE Antennas and Wireless Propagation Letters* **19**(5), 841–845.
138. **Kong D, Li H, Luo Q and Gao S** (2020) Electronically beam-scanning antenna with active slot frequency selective surface for 5-G base stations. In *IEEE MTT-S International Wireless Symposium (IWS), 2020*. IEEE Publications, 1–3.
139. **Shuai K, Yang J, Liu C, Yang X and Liu X** (2021) Beam-steering transmit array with active frequency selective surface for wireless power transmission. *International Journal of RF and Microwave Computer-Aided Engineering* **31**(12), e22907.
140. **Deng F, Xi X, Li J and Ding F** (2014) A method of designing a field-controlled active frequency selective surface. *IEEE Antennas and Wireless Propagation Letters* **14**, 630–633.
141. **Pan W, Huang C, Chen P, Pu M, Ma X and Luo X** (2013) A beam steering horn antenna using active frequency selective surface. *IEEE Transactions on Antennas and Propagation* **61**(12), 6218–6223.
142. **Singh D and Yadav RP** (2020) A 3-D printed square loop frequency selective surface for harmonic radar applications. *Journal of Electromagnetic Waves and Applications* **34**(3), 396–406.
143. **Naqvi AH and Lim S** (2019) A beam-steering antenna with a fluidically programmable metasurface. *IEEE Transactions on Antennas and Propagation* **67**(6), 3704–3711.
144. **Sangeethalakshmi K, Rukmani Devi SR, Gangatharan N and Sivalakshmi P** (2021) Challenges and opportunities in frequency selective surfaces for EMI shielding application: A theoretical survey. *Materials Today: Proceedings* **43**, 3947–3950.

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