



Lightweight frequency selective surface prototypes based on MXene-coated 3D-printed dielectric structures

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ABSTRACT

Conventional methods for fabricating frequency selective surfaces (FSSs), such as photolithography and metal deposition, typically require rigid substrates and high-cost equipment, thereby limiting scalability and design flexibility. As a promising alternative, 3D printing enables rapid and lightweight prototyping of geometrically complex FSSs using polymeric materials; however, their inherently poor electrical conductivity restricts their direct application in high-frequency regimes. In this study, we present a hybrid fabrication strategy that combines stereolithographic (SLA) 3D printing with dip-coating using $\text{Ti}_3\text{C}_2\text{T}_x$ MXene, enabling the production of structurally robust and electrically conductive FSSs without the need for conventional metallisation. A hexagonal Y-slot bandpass FSS was fabricated using five dip-coating cycles, achieving a 99% reduction in weight compared to a copper-coated weights, while retaining excellent electromagnetic performance, featuring a resonance at 11.2 GHz, an insertion loss of 0.743 dB, and a return loss of 21.1 dB. The proposed method offers a scalable and cost-effective route for realising lightweight FSSs and demonstrates significant potential for integration into weight-sensitive electromagnetic platforms such as satellites, unmanned aerial vehicles, and aerospace radomes.

1. Introduction

Frequency selective surfaces (FSSs) are periodic structures that filter electromagnetic (EM) waves based on their frequency, acting as spatial filters with applications in radar systems, wireless communications, electromagnetic shielding, and stealth technologies [1–13]. Typically consisting of metallic patterns—such as dipoles, rings, or patches—on a dielectric substrate, FSSs can be engineered to exhibit either bandpass or bandstop characteristics, depending on their geometry and configuration [14]. The increasing use of high-frequency systems in modern applications, including 5G, satellite communications, and unmanned aerial vehicles (UAVs), has led to growing interest in compact, lightweight, and high-performance FSS designs.

Traditionally, FSS structures are fabricated using printed circuit board (PCB) techniques or metallic sheets, most often utilising materials like copper or aluminium for their high electrical conductivity [15–18].

While these conventional approaches provide excellent electromagnetic performance, they introduce notable limitations. The use of bulk metals significantly increases the overall weight, which can be detrimental in aerospace or portable applications. Moreover, the inherent rigidity of metallic components restricts design flexibility, particularly in conformal or adaptive surfaces. Fabrication methods such as photolithography or chemical etching also require cleanroom environments and are often time-consuming and costly, particularly when prototyping or manufacturing custom geometries.

To overcome these challenges, recent research has explored the integration of additive manufacturing (AM) techniques into FSS design [19–22]. In particular, stereolithography (SLA)—a high-resolution 3D printing technique—enables the fabrication of complex and lightweight dielectric substrates using polymer-based resins [23–26]. These materials offer excellent mechanical precision and substantial weight advantages, making them highly attractive for next-generation

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electromagnetic components [27–34]. However, a fundamental limitation of polymer-based 3D-printed structures is their inherent lack of electrical conductivity. Without further metallisation, these substrates cannot function effectively as FSSs.

To impart conductivity to 3D-printed parts, various metallisation methods have been explored, including metal sputtering, electroless plating, and the application of conductive paints. For instance, silver nanoparticle-based inks and copper electroplating have been employed to coat polymer substrates [35]. While these techniques can yield high conductivity, they often involve complex, multi-step processes, require specialised equipment, or result in coatings with poor mechanical flexibility or adhesion. Additionally, the addition of metallic layers may offset the lightweight benefits of polymer-based 3D printing, thus undermining one of its key advantages.

Recent advancements in nanomaterials have introduced MXenes—a family of two-dimensional transition metal carbides, nitrides, and carbonitrides—as promising candidates for flexible, scalable, and solution-processable conductive coatings [36–40]. Among them, $\text{Ti}_3\text{C}_2\text{T}_x$ MXene has attracted particular interest due to its high electrical conductivity (up to 24,000 S/cm) [41], hydrophilic nature, and ease of processing through straightforward methods such as dip-coating or spray-casting [42]. In contrast to traditional metal coatings, MXenes can form uniform, conductive films on a range of substrates at room temperature, without the need for vacuum systems or high-temperature sintering [43,44]. These properties make MXenes especially compatible with polymer-based 3D-printed structures, offering a low-cost, lightweight solution for electromagnetic device fabrication [29,42,45].

Several prior studies have demonstrated the effective use of MXenes in electromagnetic interference (EMI) shielding, antennas, and waveguides, as well as in absorber-based frequency-selective structures that exploit the intrinsic electromagnetic loss characteristics of MXenes [41,42,46–49]. These works clearly establish MXenes as highly promising materials for electromagnetic wave manipulation and provide an important foundation for frequency-dependent electromagnetic design. Building upon these advances, further opportunities exist to extend MXene-based frequency-selective structures toward lightweight and geometrically complex architectures enabled by additive manufacturing. In particular, the application of MXene coatings to three-dimensional, additively manufactured FSSs has not yet been extensively explored. Moreover, there is still a need to systematically investigate the electromagnetic performance and structural robustness of MXene-coated 3D-printed FSSs, particularly under multiple coating cycles and realistic fabrication conditions.

In this work, we address these limitations by proposing a lightweight, bandpass-type FSS structure fabricated using SLA 3D printing and dip-coated with $\text{Ti}_3\text{C}_2\text{T}_x$ MXene. The FSS geometry was carefully optimised to maximise the conductive surface area, thereby enhancing compatibility with the dip-coating process. SLA printing was selected due to its high resolution and capability to produce the fine structural features required for effective FSS elements. A total of five dip-coating cycles were performed to achieve a uniform and conductive MXene film over the 3D-printed polymer surface.

Compared to conventional copper-based FSS structures, our prototype exhibited a 99% reduction in coating weight while maintaining strong electromagnetic performance, including a resonant frequency of 11.2 GHz, an insertion loss of 0.743 dB, and a return loss of 21.1 dB. These results confirm the feasibility of employing MXene-coated, 3D-printed structures as a viable alternative to traditional metallic FSSs, especially in applications where weight, cost, and design flexibility are paramount. Furthermore, our approach leverages a simple and scalable fabrication process that avoids vacuum deposition and complex surface treatments, enabling rapid prototyping and wider accessibility.

2. Results and discussion

2.1. Fabrication of FSS

Fig. 1(a) illustrates the working principle of SLA printing using the Formlabs 4 L printer. SLA is a high-resolution additive manufacturing technique that fabricates three-dimensional structures through the layer-by-layer photopolymerisation of liquid resins. The process operates by directing a focused ultraviolet (UV) laser onto a photocurable resin, selectively curing specific regions to form solidified layers that collectively define the target geometry. During the SLA process, the build platform is initially positioned just above the resin surface inside a vat filled with liquid photopolymer. A UV laser or digitally projected light pattern then scans the cross-sectional area of the current layer, initiating polymerisation in the exposed regions. Upon completion of each layer, the platform moves vertically, typically in the Z-direction, allowing uncured resin to flow over the solidified structure before exposing the next layer. This sequence is repeated iteratively until the entire 3D object is fabricated. Compared to other 3D printing methods such as fused deposition modelling (FDM) or selective laser sintering (SLS), SLA offers a superior surface finish, high dimensional accuracy (typically within tens of micrometres), and the capability to produce intricate geometries with fine features. Fig. 1(b) presents the post-processing workflow for SLA-printed parts. After designing the 3D model, it is exported to the printer for fabrication. During setup, it is recommended to orient the print at an angle of approximately 20° to enhance print accuracy and minimise support artefacts. Upon completion, the printed object is washed in a cleaning station using isopropyl alcohol (IPA) for around 10 min to remove residual uncured resin. The part then undergoes a two-step curing process: an initial UV cure at 80°C for 120 min, followed by thermal curing in a convection oven at 160°C for 180 min. This extended curing sequence significantly increases the heat deflection temperature of the printed part, reaching up to 238°C , thereby enabling it to withstand high-temperature post-treatments.

2.2. Synthesis and analysis of MXene

$\text{Ti}_3\text{C}_2\text{T}_x$ MXene was synthesized from the Ti_3AlC_2 MAX phase using the minimally intensive layer delamination (MILD) method via an in-situ LiF/HCl etching route (detailed in the Experimental Section). This method is advantageous over conventional HF etching due to its milder reaction conditions, improved safety, and higher colloidal stability of the final MXene dispersion. The successful etching and structural transformation from MAX to MXene were confirmed by X-ray diffraction (XRD). As shown in the XRD pattern (Fig. 2(a)), the characteristic (002) peak of Ti_3AlC_2 at $\sim 9.43^\circ$ shifts to a lower angle ($\sim 6.03^\circ$) after etching, which is indicative of an increase in interlayer spacing due to the removal of Al layers [50]. This shift confirms the formation $\text{Ti}_3\text{C}_2\text{T}_x$ MXene with expanded basal spacing, a key feature of successful MXene synthesis. Transmission electron microscopy (TEM) further validates the structural integrity and morphology of the delaminated MXene flakes (Fig. 2(b)). The TEM image reveals ultrathin, well-exfoliated, transparent flakes, indicative of high-quality well delaminated MXene. The inset selected area electron diffraction (SAED) pattern displays sharp hexagonal diffraction spots, confirming the preserved crystallinity and 2D symmetry of the $\text{Ti}_3\text{C}_2\text{T}_x$ flakes [51]. A dilute aqueous dispersion of $\text{Ti}_3\text{C}_2\text{T}_x$ MXene typically exhibits a greenish color (Fig. 2(c), inset). The corresponding UV–vis absorption spectrum (Fig. 2(c)) shows distinct absorption peaks at approximately 770 nm and 320 nm, which are characteristic of $\text{Ti}_3\text{C}_2\text{T}_x$ and align well with previously reported data [52].

2.3. Fabrication of MXene-coated FSS

The high-temperature resin (HT resin) FSS initially exhibits

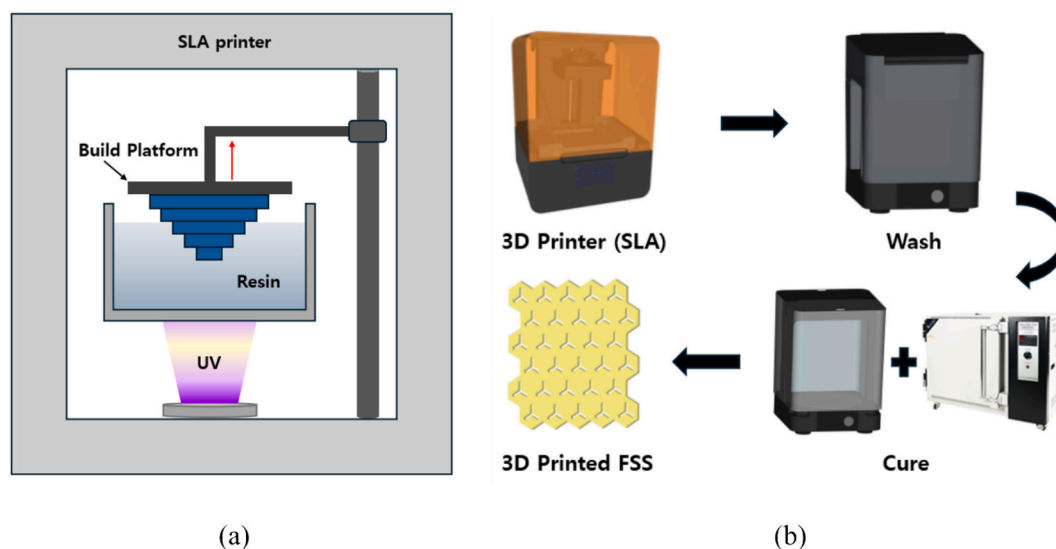


Fig. 1. Illustrations of the 3D printing process: (a) SLA 3D printing overview; (b) step-by-step manufacturing process of the FSS.

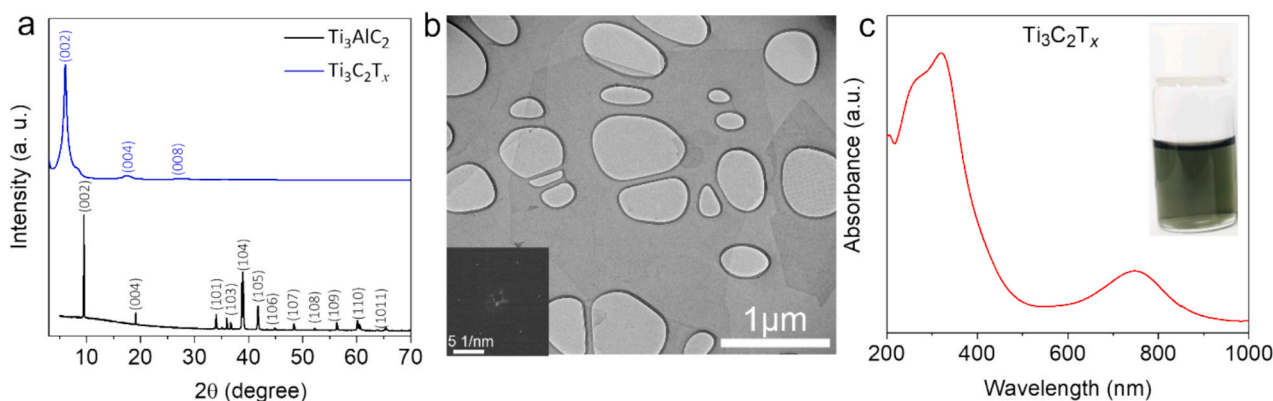


Fig. 2. Synthesis and characterization of $\text{Ti}_3\text{C}_2\text{T}_x$ MXene: (a) XRD patterns of Ti_3AlC_2 MAX phase and etched $\text{Ti}_3\text{C}_2\text{T}_x$ MXene, showing the characteristic (002) peak shift indicative of successful etching and delamination; (b) TEM image of a single-layer MXene flake with corresponding selected area electron diffraction (SAED) pattern (inset), confirming crystallinity and flake morphology; (c) UV-Vis absorption spectrum of $\text{Ti}_3\text{C}_2\text{T}_x$ MXene dispersion, with the inset showing a photograph of the stable aqueous colloidal solution.

hydrophobic characteristics, hindering its compatibility with hydrophilic MXenes. To address this, a 10-minute UV-ozone treatment is applied via UV-ozone cleaner (AC-3), introducing oxygen-containing polar groups ($-\text{COOH}$, $-\text{OH}$, $\text{C}=\text{O}$) onto the resin surface, thereby improving its hydrophilicity and enabling better interaction with aqueous solutions (Fig. 3(a)) [53]. Subsequently, the resin undergoes 3-Aminopropyl triethoxysilane (APTES) treatment in a toluene solution for 20 min (Fig. 3(b)). This step serves two key functions: it removes organic surface contaminants and introduces amine ($-\text{NH}_2$) functionalities. APTES hydrolyzes to form silanol groups that covalently bond ($\text{Si}-\text{O}-\text{Si}$) with hydroxyl groups on the ozone-treated surface [54]. The exposed $-\text{NH}_2$ groups promote strong electrostatic and hydrogen bonding interactions with negatively charged MXene surface [51,55]. Together, the UV-ozone and APTES treatments synergistically enhance surface wettability, chemical reactivity, and adhesion, making the substrate more compatible for subsequent MXene coating processes [56]. The effectiveness of the surface modification was further confirmed by water contact angle measurements, as shown in Fig. 3(c). The contact angle of the untreated HT resin surface was measured to be 77.9° , whereas it decreased to 65.4° after sequential UV-ozone and APTES treatment, indicating a significant improvement in surface hydrophilicity.

Fig. 4(a) illustrates the dip coating process and Fig. 4(b) illustrates

underlying principles. Dip coating is a versatile and scalable technique widely used to fabricate functional thin films on three-dimensional or irregularly shaped substrates. In this study, the dip coating method was employed to uniformly deposit a conductive MXene layer onto a 3D-printed FSS, fabricating a lightweight, high-performance electromagnetic structure. The coating procedure consists of the following steps:

- **Step 1 – Ozone surface treatment:** To improve surface wettability and adhesion, the FSS substrate is subjected to ultraviolet ozone (UV- O_3) treatment for 10 min on each side. This treatment introduces polar functional groups (e.g., hydroxyl, carboxyl) onto the polymer surface, converting it from hydrophobic to hydrophilic.
- **Step 2 – Dip coating cycle:** The treated FSS substrate is vertically immersed in an aqueous $\text{Ti}_3\text{C}_2\text{T}_x$ MXene dispersion with a concentration of 20 mg/mL to promote effective interaction between the colloidal MXene nanosheets and the substrate surface. Each immersion step is maintained for 10 min to allow sufficient wetting and adsorption of MXene flakes, and mild agitation may be applied to ensure uniform contact across the entire structure. After immersion, the substrate is withdrawn from the dispersion, leaving a thin MXene layer on the surface through viscous drag-induced deposition. The coated sample is subsequently dried in a convection oven at a temperature between 70 and 80 $^\circ\text{C}$ for 30 min to ensure solvent

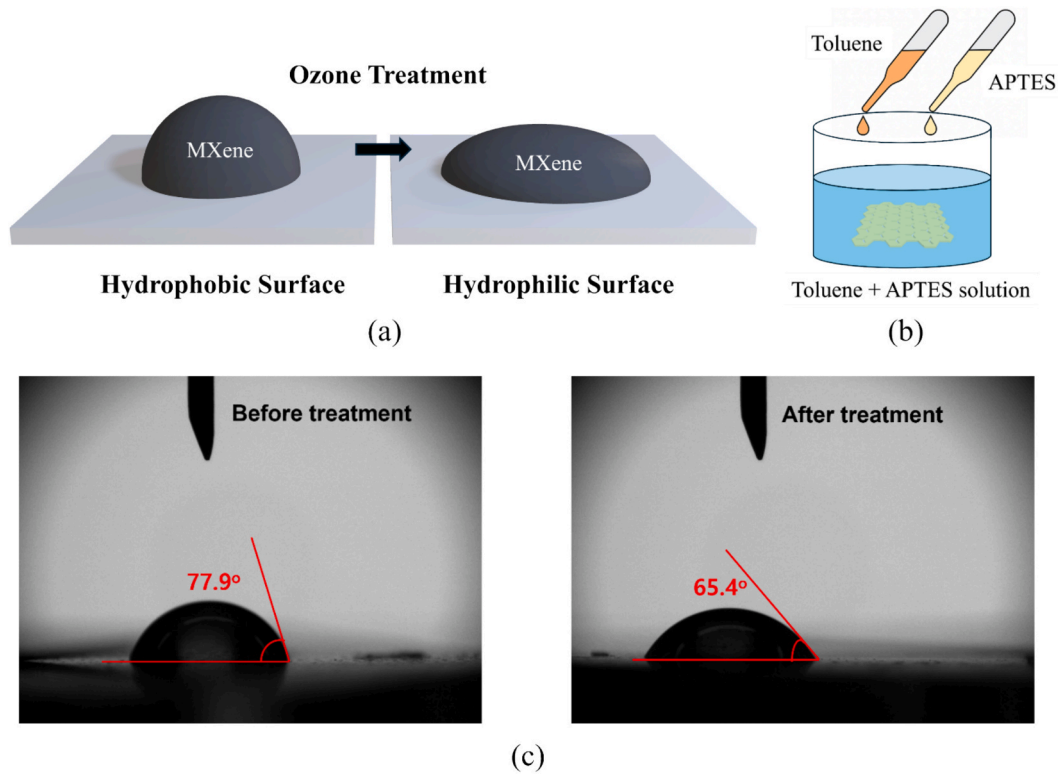


Fig. 3. Ozone surface treatment and solution treatment: (a) Transformation of hydrophobic surface to hydrophilic surface during ozone treatment; (b) Surface treatment with toluene and APTES solution; (c) Water contact angle of before UV-ozone and APTES treatment and after treatment.

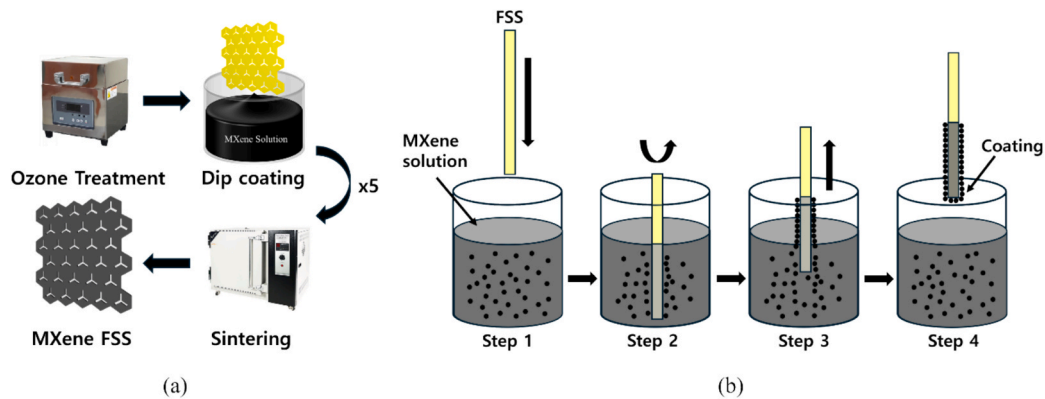


Fig. 4. Dip coating process and mechanism: (a) Five-cycle dip coating process; (b) Detailed dip coating method.

evaporation and stabilisation of the deposited MXene layer. This dip-coating and drying procedure is repeated five times to gradually build up a uniform and continuous conductive coating, thereby improving surface coverage and electrical conductivity.

- **Step 3 – Thermal sintering:** After the final dip-coating cycle, the MXene-coated FSS structures undergo an additional thermal treatment in a convection oven at a temperature between 70 and 80 °C for 30 min. This post-treatment facilitates further removal of residual solvent, promotes improved interflake contact between adjacent MXene nanosheets, and stabilises the coating morphology. As a result, the mechanical robustness and electrical performance of the MXene-coated FSS are enhanced.

Dip coating imposes geometric limitations for thick resin features and sharp corner structures, where surface-tension effects can hinder uniform MXene deposition. Surface hydrophilization of the HT resin

mitigates this issue, but extremely acute FSS geometries remain challenging for achieving fully uniform coatings.

As a prototype, we fabricated the proposed FSS consisting of 5×6 unit cells. Fig. 5 shows the appearance of the FSS after MXene coating, with Fig. 5(a) displaying the top side and Fig. 5(b) the enlarged unit cell. This FSS was produced using the process described above and has dimensions of 114.31 mm $\times$ 114 mm $\times$ 2 mm.

2.4. FSS performance

Fig. 6 depicts the measurement setup and the corresponding results. Fig. 6(a) illustrates the free-space measurement configuration used to characterise the electromagnetic performance of the fabricated FSS. A vector network analyser (Keysight N9951A) was employed, with a transmitting horn antenna (Tx) and a receiving horn antenna (Rx) aligned along the propagation axis. The fabricated sample was

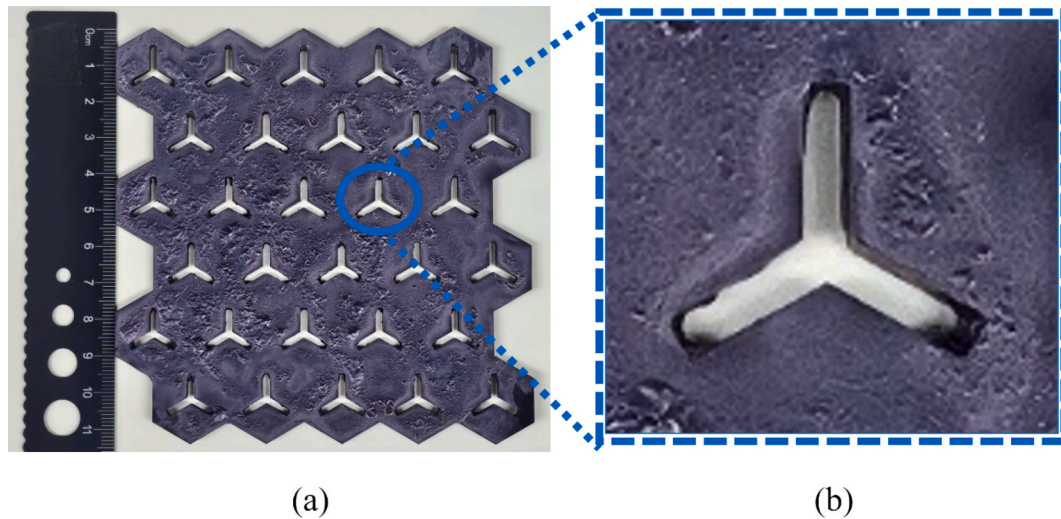


Fig. 5. Fabricated prototype MXene FSS: (a) Top view; (b) Enlarged view.

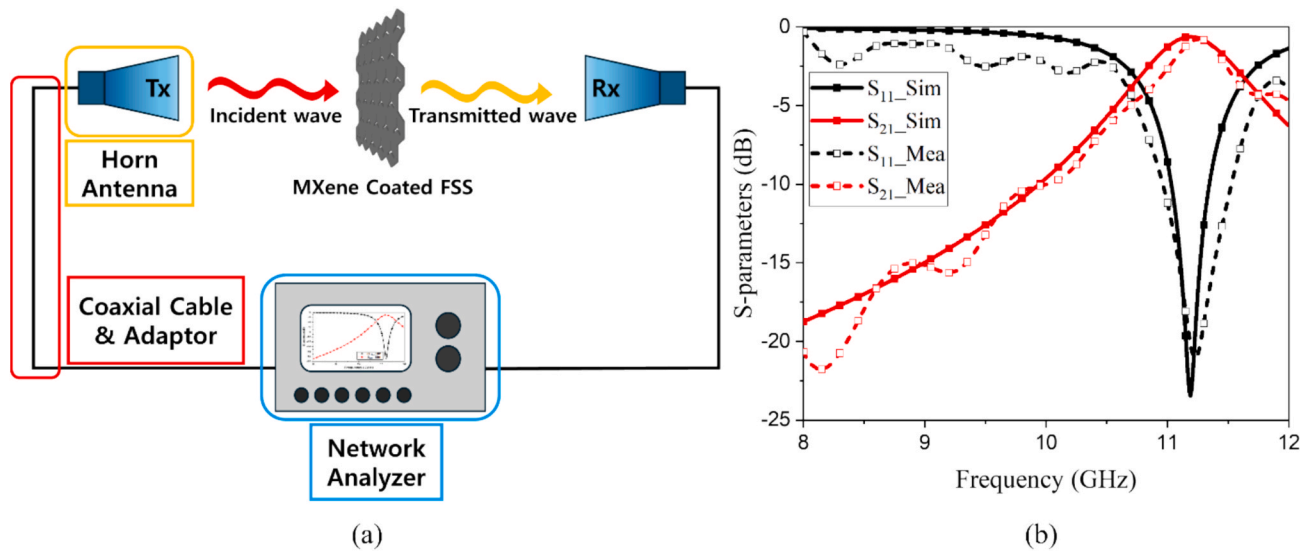


Fig. 6. Measurement setup and results: (a) experimental configuration; (b) MXene FSS measurement results.

positioned vertically at the midpoint between the Tx and Rx antennas to ensure normal incidence of the electromagnetic waves. The horn antennas were connected to the calibrated VNA, with Port 1 assigned to Tx and Port 2 to Rx. A full two-port calibration was performed to eliminate systematic errors and enhance the accuracy of the measured scattering parameters. The transmission coefficient (S_{21}) and reflection coefficient (S_{11}) were recorded across the frequency range of interest. As shown in Fig. 6(b), the measured S-parameters exhibit a distinct resonant behaviour, confirming the designed frequency-selective characteristics of the FSS. These results demonstrate that the proposed structure operates effectively within the specified frequency band.

Fig. 7 shows an FSS fabricated using copper tape and its simulated S-parameters. Fig. 7(a) and 7(b) present the unit cell patterned on a dielectric substrate by manually attaching copper tape to a geometry designed identically to the MXene FSS. The structure consists of periodic resonant elements arranged in a hexagonal lattice. Scale bars indicating the physical dimensions of the fabricated sample are included for reference. The simulated reflection (S_{11}) and transmission (S_{21}) coefficients, alongside a zoomed-in view of the transmission coefficient, are displayed in Fig. 7(c). The results clearly indicate resonance near the designed operating frequency. For comparison, the S-parameters

simulated for the MXene-coated surface are also included.

Fig. 8 presents a comparative analysis of simulated and measured S-parameters for copper- and MXene-based FSS structures, as well as a long-term stability evaluation of the MXene-based FSS over 30 days. Fig. 8(a) shows the simulated reflection (S_{11}) and transmission (S_{21}) coefficients for the copper-based structure (blue curves) and the MXene-based structure (red curves). At the designed resonant frequency of 11.2 GHz, the copper-based FSS exhibits an S_{11} of -29.24 dB and an S_{21} of -0.316 dB, indicating strong reflection and minimal transmission loss. In simulation, the MXene-based FSS demonstrates an S_{11} of -23.46 dB and an S_{21} of -0.617 dB, showing comparable performance despite employing a non-metallic conductive material. The measured S-parameters of the MXene-based FSS reveal an S_{11} of -21.1 dB and an S_{21} of -0.743 dB at 11.2 GHz, confirming the high fidelity of the fabricated prototype relative to simulation and validating the applicability of MXene materials in high-frequency FSS designs. Fig. 8(b) displays the temporal stability of the MXene-coated FSS by comparing S-parameters measured on Days 1 and 30 under ambient conditions. Although slight variations in the magnitudes of S_{11} and S_{21} occur over time, the overall resonant characteristics remain largely intact. These findings indicate that the MXene-based FSS maintains functional stability throughout the

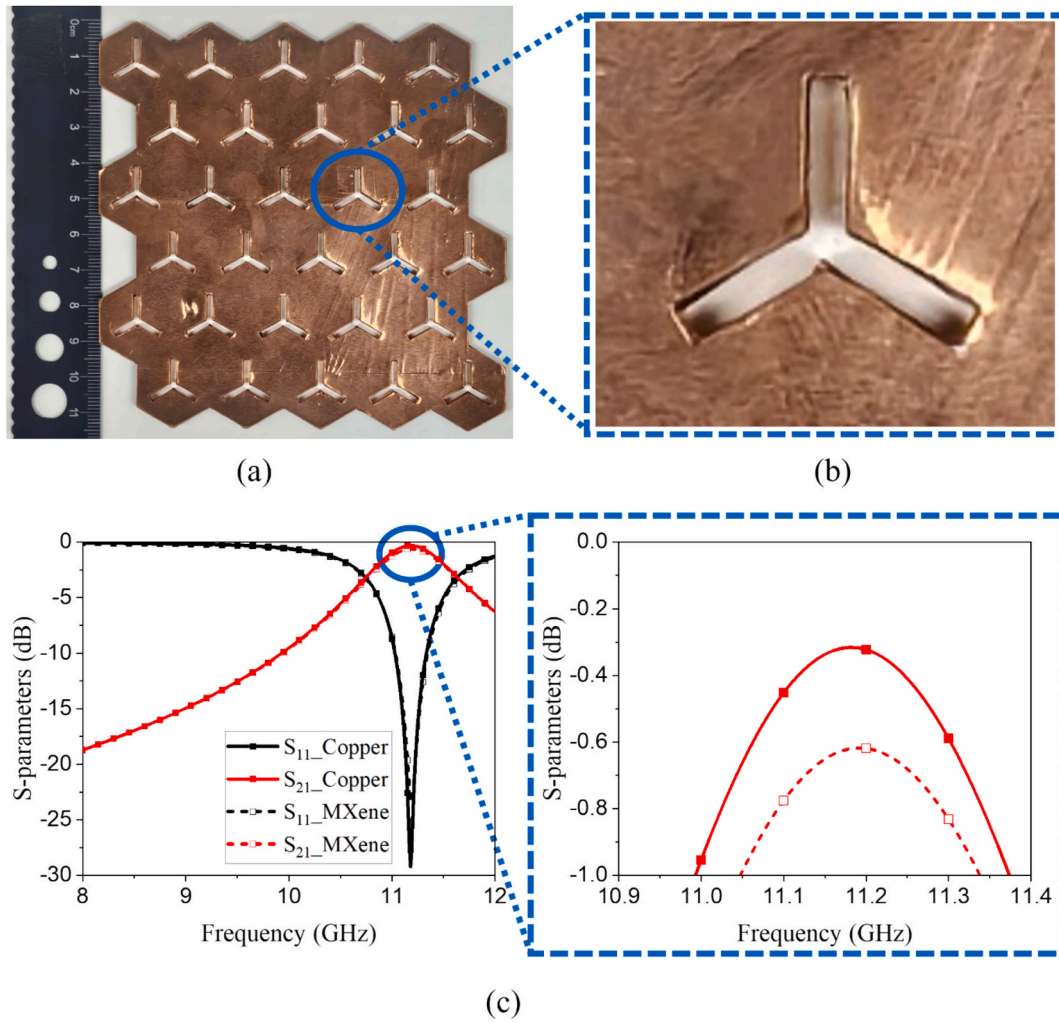


Fig. 7. Copper tape fabricated FSS and simulation results: (a) top view; (b) Enlarged view; (c) comparison of simulation results for copper FSS and MXene FSS.

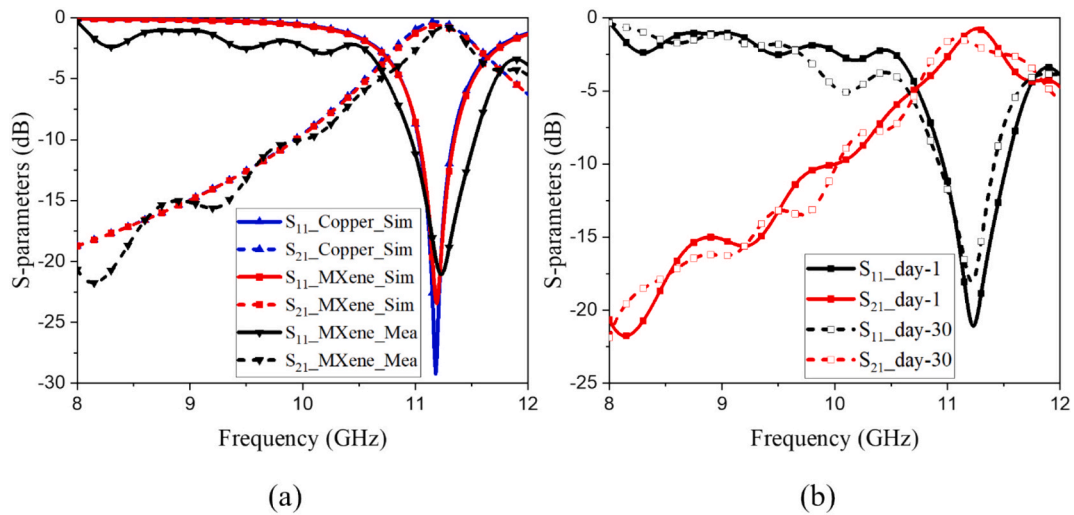


Fig. 8. (a) Simulated and measured S-parameters comparison; (b) MXene FSS stability over 30 days.

test period, supporting its potential for practical electromagnetic applications.

Fig. 9(a) shows the variation in coating thickness as a function of the number of dip-coating cycles. In a single cycle, the coating thickness was

13 μm . As the number of coating cycles increased, the thickness rose gradually: 20 μm after two cycles, 25 μm after three, 27.5 μm after four, and finally 36.5 μm after five cycles. Fig. 9(b) presents the sheet resistance in relation to the number of coatings, as well as the sheet

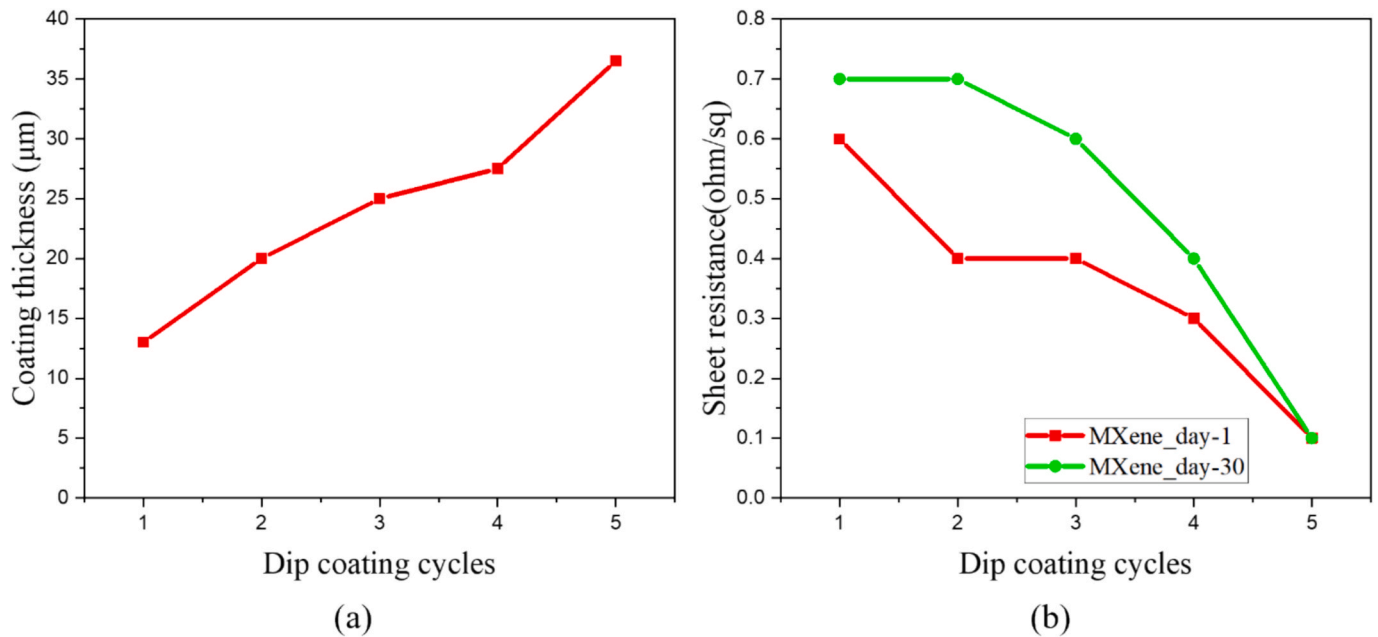


Fig. 9. Analysis of MXene coating thickness, sheet resistance, and stability: (a) measured thickness of MXene for different dip-coating cycles; (b) sheet resistance for various coating cycles and after 30 days.

resistance measured after 30 days. Initially, the sheet resistance was 0.6 Ω/sq for one dip-coating cycle. As the number of coating cycles increased, the sheet resistance decreased progressively: 0.4 Ω/sq after two cycles, remaining 0.4 Ω/sq after three cycles, 0.3 Ω/sq after four, and 0.1 Ω/sq after five cycles. After 30 days, measurements indicated a slight increase for samples with fewer coatings: 0.7 Ω/sq for one and two cycles, 0.6 Ω/sq for three, 0.4 Ω/sq for four, and stability was maintained at 0.1 Ω/sq for five cycles. These results demonstrate that the sheet resistance remained relatively stable over time, with minimal degradation observed, particularly for samples subjected to multiple coating cycles.

Fig. 10 presents weight measurements of three FSS samples fabricated on the same dielectric substrate: a bare (uncoated) substrate, an MXene-coated FSS, and a copper-taped FSS. The weight of each sample was measured using a precision electronic balance, with the values displayed beneath each sample. As shown in Fig. 10(a)–(c), the bare substrate weighs 28.20 g, while the MXene-coated sample weighs 28.30 g, indicating a negligible increase of only 0.1 g. This minimal weight gain results from the ultra-thin MXene layer formed via the dip-coating process. In contrast, the FSS using copper tape shows a weight increase of 10.31 g from 28.2 g to 38.51 g due to the significant mass of the copper adhesive layer. The bar graph in Fig. 10(d) provides a visual

comparison, clearly demonstrating the lightweight advantage of the MXene-coated FSS over its copper-based counterpart. This considerable weight reduction—approximately 99% compared to the copper-coated weights—not only facilitates structural integration but also reduces mechanical stress and material costs. The lightweight nature of MXene-coated FSS structures is particularly advantageous in weight-sensitive applications such as aerospace platforms, unmanned aerial vehicles (UAVs), satellites, and wearable or conformal electromagnetic systems. In these domains, minimising mass directly translates to improved payload efficiency, enhanced manoeuvrability, and reduced energy consumption. Therefore, MXene-based coatings offer a promising pathway towards the development of high-performance yet lightweight electromagnetic components for next-generation wireless and sensing systems.

2.5. Simulation comparison

Fig. 11(a) illustrates the overview of the proposed FSS. The structure comprises a hexagonal dielectric substrate featuring a Y-shaped slot with three legs. Fig. 11(b) depicts the unit cell without MXene coating, while Fig. 11(c) shows the MXene-coated version. The FSS is 3D printed using high-temperature (HT) resin, a heat-resistant polymer material with a

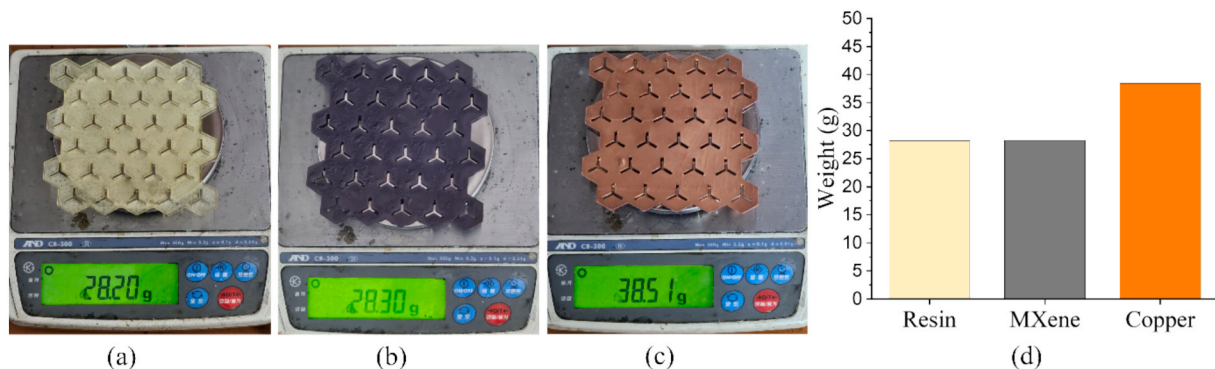


Fig. 10. Weight comparison of resin FSS, MXene-coated FSS, and copper FSS: (a) 3D printed FSS weight; (b) MXene-coated FSS weight; (c) copper tape FSS weight; (d) comparative weight graph.

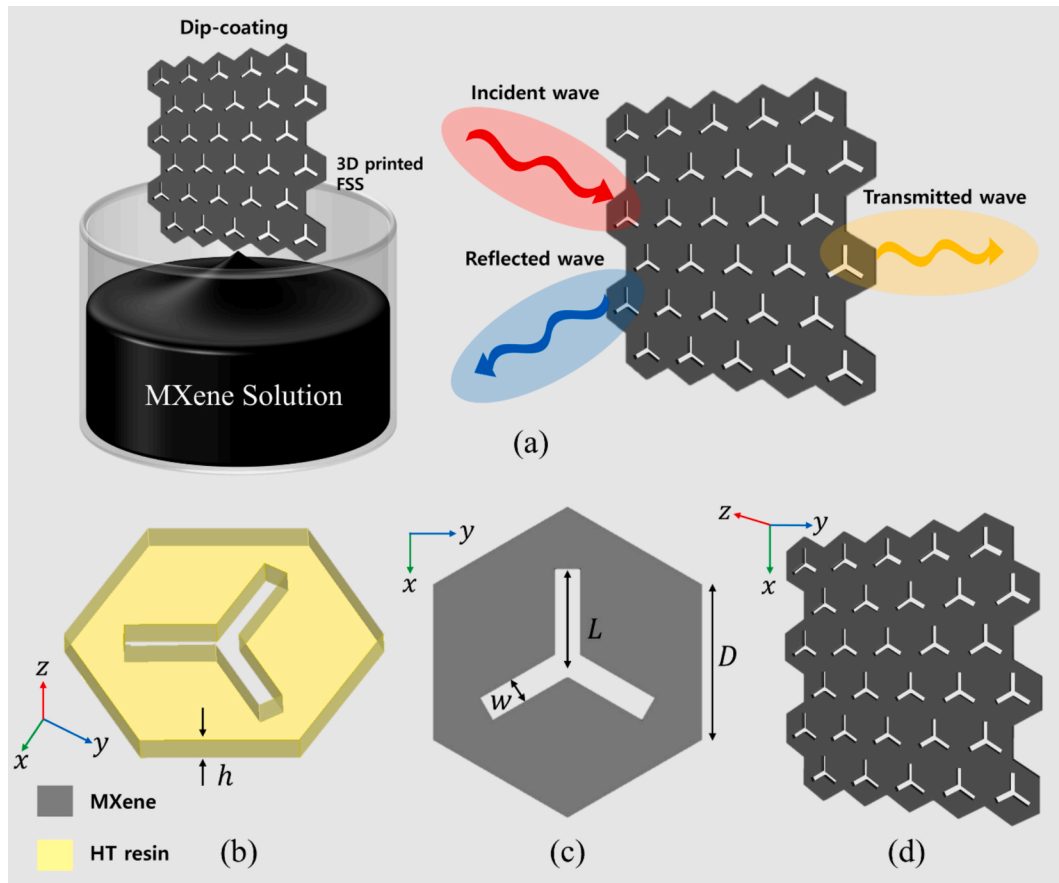


Fig. 11. (a) Conceptual illustration, Unit cell design and geometry; (b) unit cell without MXene; (c) top view of MXene-coated unit cell; (d) full structure.

dielectric constant of 2.5 and a loss tangent of 0.02. Electrical conductivity is imparted via a dip-coated MXene layer. In simulations, the MXene coating is modelled as an impedance boundary. To simplify the design, the unit cell parameters were fixed with length D , while the slot length (L) and slot width (w) of the Y-shaped slot were adjusted to produce a stable passband. The key dimensions are: $D = 12$ mm, $L = 6.75$ mm, $w = 2$ mm, and $h = 2$ mm. The thickness h typically falls between $\lambda_0/20$ and $\lambda_0/10$. Fig. 11(d) presents the overall array layout,

which comprises 30 unit cells in a 5×6 arrangement, resulting in an overall size of 114.31 mm $\times$ 114 mm. The structure was designed and simulated using ANSYS high frequency structural simulator (HFSS), and fabricated using a Formlabs 4 L SLA 3D printer.

To analyse the electromagnetic behaviour of the periodic structure, Floquet's theorem was applied. This theorem asserts that in a spatially periodic medium, the electromagnetic field can be expressed as the product of a plane wave and a periodic function, leading to the concept

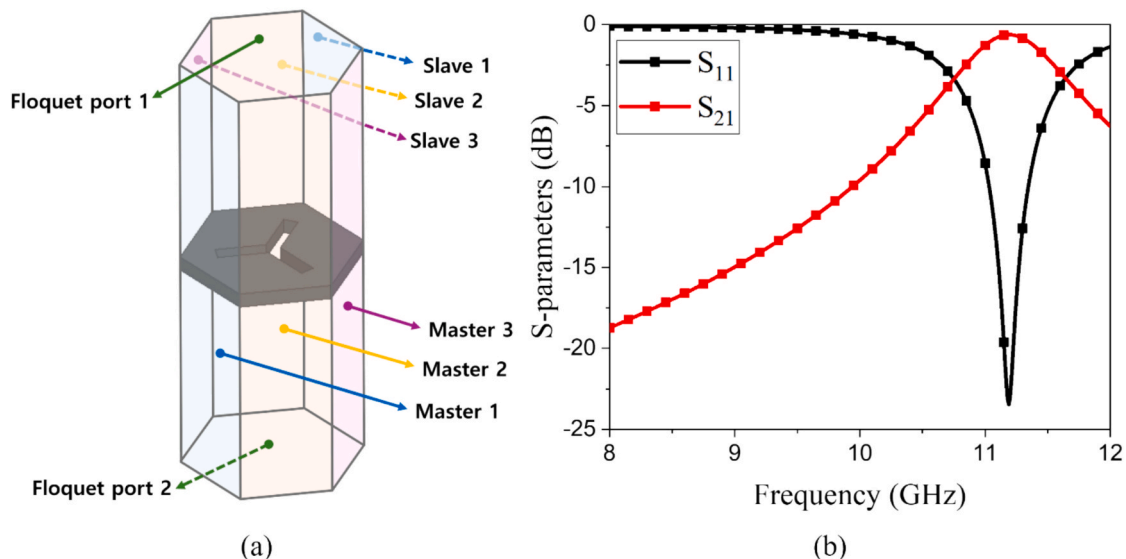


Fig. 12. Unit cell simulation setup and results: (a) boundary conditions and excitation ports; (b) simulated result of MXene-coated FSS.

of Floquet modes. These modes describe the spatial harmonics arising from periodicity and are crucial for understanding scattering and transmission characteristics. Floquet ports were implemented in the HFSS simulations to enable this analysis.

Fig. 12(a) shows the boundary conditions and port configuration. To simulate periodic behaviour, three pairs of master/slave boundaries were defined, along with Floquet ports. The master and slave faces were paired under the assumption that the electromagnetic field on the slave face replicates the master face with a phase shift, reflecting the structure's spatial periodicity. This method enables accurate prediction of the array's performance based on a single unit cell, eliminating the need to model the full array. Fig. 12(b) presents the simulation results for the MXene-coated FSS, showing a return loss of 23.46 dB and an insertion loss of 0.617 dB at a resonant frequency of 11.2 GHz. The simulated bandwidth spans 820 MHz, from 10.79 to 11.61 GHz.

Parametric studies were conducted to assess the effects of various parameters, including slot width, slot length, substrate thickness, and surface impedance, on the FSS performance. As shown in Fig. 13(a), the FSS response is largely insensitive to changes in substrate thickness, indicating minimal influence on electromagnetic behaviour. To account for conductive losses in the MXene coating, an impedance boundary condition was applied, with surface resistance values used to approximate realistic conduction characteristics of thin metal or conductive films. As shown in Fig. 13(b), increasing the surface impedance from 0.4 to 1.9 Ω/sq leads to a rise in insertion loss from 0.617 to 2.82 dB, and a decrease in return loss from 23.46 to 11.5 dB. Fig. 13(c) demonstrates the influence of slot width: as the width increases from 1.6 mm to 2.2 mm, the bandwidth broadens from 650 to 870 MHz. Fig. 13(d)

illustrates the effect of slot length on the resonant frequency. Increasing slot length reduces the resonant frequency, as a longer slot corresponds to a longer resonant wavelength. Conversely, shorter slots yield higher resonant frequencies. For instance, the resonance shifts from 11.52 GHz at a length of 6.5 mm to 10.48 GHz at 7.25 mm.

The interaction effects among geometric parameters were systematically investigated through combined parametric studies, as shown in Fig. 14(a)–(d). As illustrated in Fig. 14(a), the coupled variation of substrate thickness and slot width results in only minor changes in the resonance characteristics of the FSS, indicating that these two parameters have a relatively weak influence on the overall bandpass response within the investigated ranges. Similarly, the combined effect of slot width and slot length presented in Fig. 14(b) reveals that variations in slot width primarily modulate the response, while the resonance behavior is largely governed by the slot length. The interaction between slot length and substrate thickness is further examined in Fig. 14(c), where changes in substrate thickness again lead to limited variation in the FSS performance compared to the pronounced effect induced by variations in slot length. In all coupled two-parameter cases, a consistent trend is observed in which a reduction in slot length leads to a gradual degradation of the bandpass performance, accompanied by a shift in the resonance condition. Furthermore, the simultaneous three-parameter variation shown in Fig. 14(d) confirms that, although interaction effects among slot width, slot length, and substrate thickness exist, they do not override the dominant role of the slot length. Instead, variations in slot width and substrate thickness primarily act as secondary tuning factors that modulate the FSS response around a resonance condition fundamentally determined by the slot length. These results demonstrate

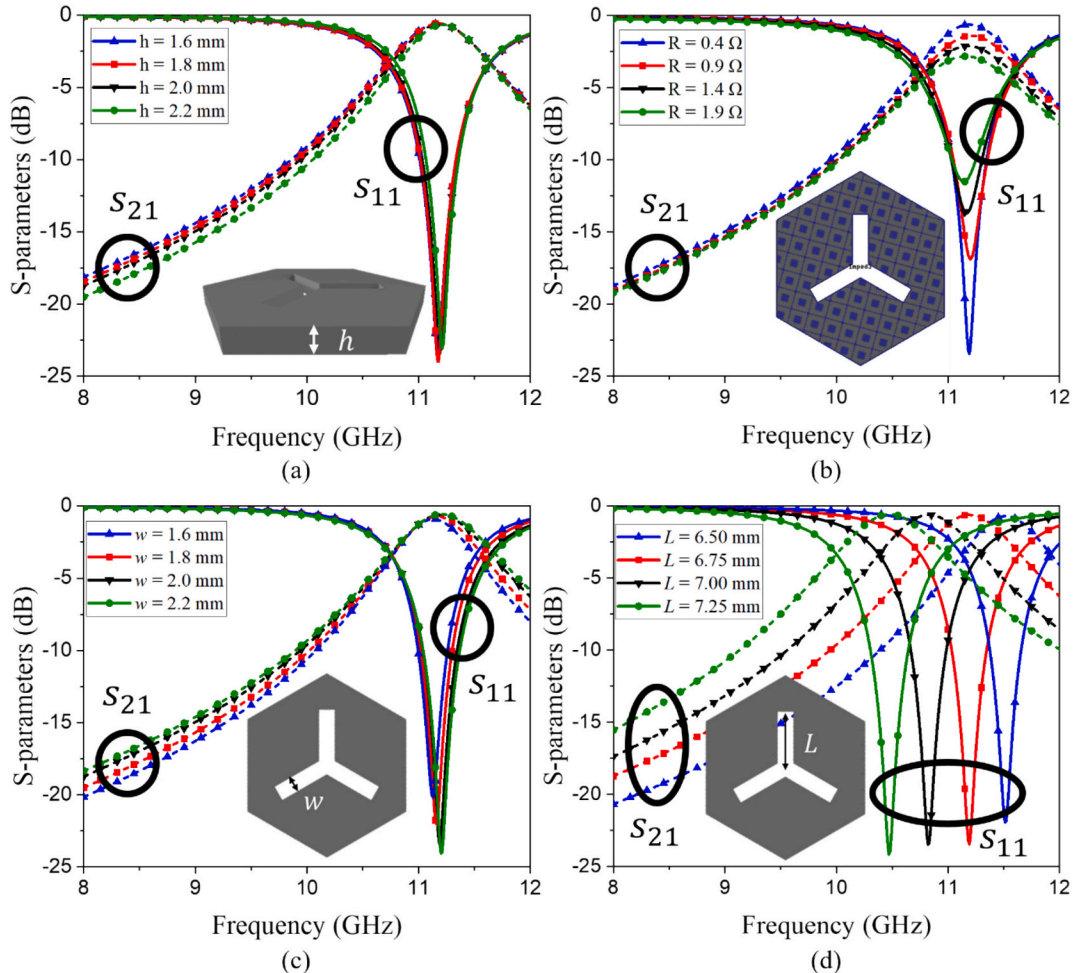


Fig. 13. Parametric simulation results for: (a) substrate thickness; (b) surface impedance; (c) Y-slot width w ; (d) Y-slot length L .

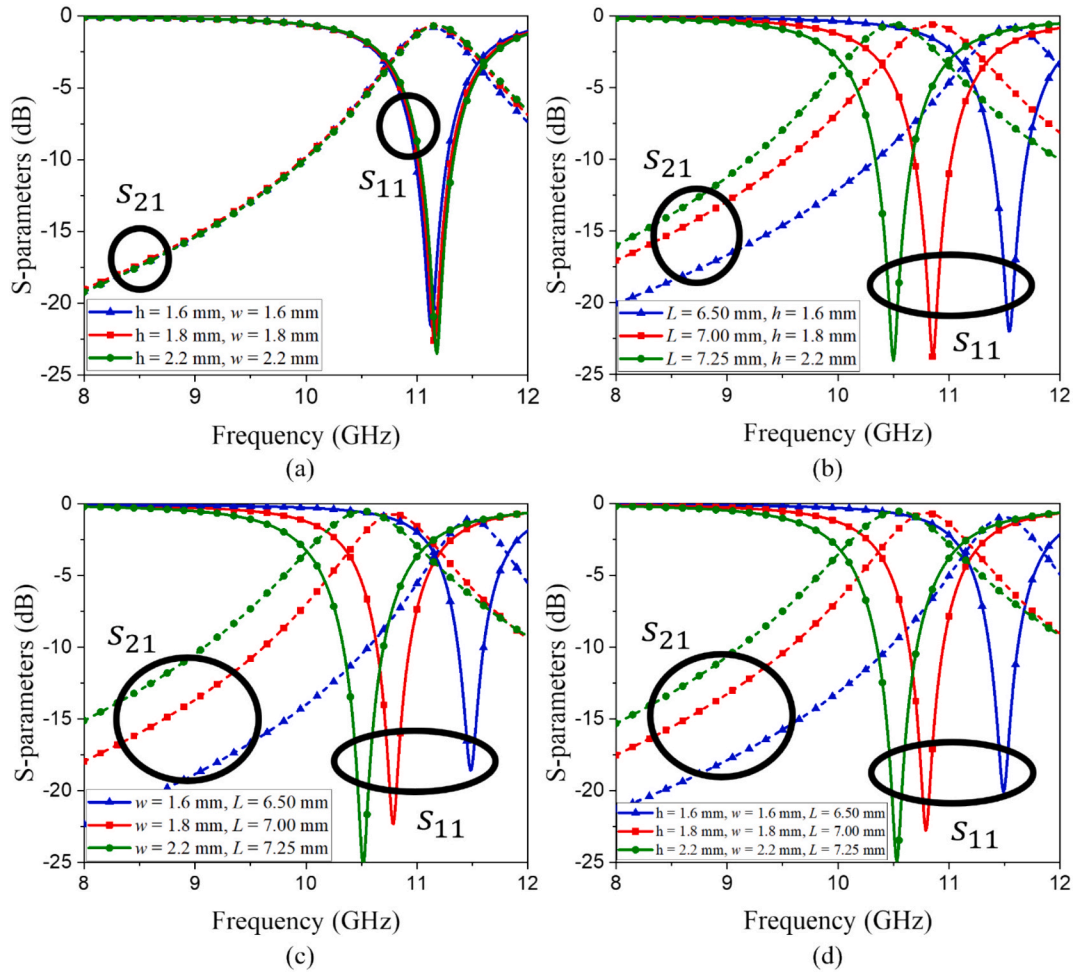


Fig. 14. Parametric interaction analysis of the proposed FSS under combined variations of geometric parameters: (a) Coupled effect of substrate thickness and slot width; (b) coupled effect of slot width and slot length; (c) coupled effect of slot length and substrate thickness; and (d) simultaneous variation of slot length, slot width, and substrate thickness.

that the slot length serves as the primary design parameter for controlling the FSS performance, while the substrate thickness and slot width can be considered secondary parameters for fine adjustment and structural optimization.

The proposed FSS can be represented by an equivalent RLC circuit, which is derived from both the geometry of the unit cell and the electromagnetic behaviour of the Y-shaped slot. Fig. 15 illustrates the simulated electric field (E-field) distribution, along with the corresponding equivalent circuit, for both the front and rear surfaces of the unit cell. In Fig. 15(a), the E-field is strongly concentrated at the ends and junction of the Y-slot, indicating the presence of significant current accumulation at resonance. Fig. 15(b) shows that the electromagnetic field is similarly concentrated in the vicinity of the slot, where the gap within the slot is modelled as a capacitance (C). The loop formed by the Y-shaped slot is represented as an inductance (L), while losses, including those due to surface resistance, are accounted for by a resistance (R). The resonance frequency is governed by the values of L and C , and is given by the following expression:

$$f = \frac{1}{2\pi\sqrt{LC}} \quad (1)$$

The extracted parameter values are: $C = 0.842$ pF, $L = 0.24$ nH, and $R = 0.11$ Ω . These values, along with the circuit simulation, were obtained using the advanced design system (ADS) software. As shown in Fig. 15(c), the scattering parameters derived from the equivalent circuit closely correspond to those obtained from the full-wave simulation, thereby

validating the accuracy of the circuit model. In addition to the magnitude responses, the phase characteristics of the proposed equivalent circuit (EC) model were further investigated to provide a more rigorous validation. Fig. 15(d) presents a comparison of the phase responses of S_{11} and S_{21} obtained from full-wave electromagnetic simulations using HFSS and circuit-level simulations using ADS. As observed, the phase responses from the EC model show excellent agreement with those from the full-wave simulations over the entire frequency range of interest. This strong correlation in both magnitude and phase responses confirms that the proposed EC model accurately captures the underlying resonance behavior and reactive characteristics of the MXene-coated FSS.

A quantitative comparison with representative lightweight Frequency selective surfaces (FSSs) reported in the literature is presented in Table 1, including center frequency, total weight, fabrication process, unit size, cost level, and S-parameter performance. This comparison provides a clear basis for evaluating the practical advantages of the proposed approach. As summarized in Table 1, screen-printed three-layer FSSs [12] and silver-coated Aramid honeycomb FSSs [13] employ low-cost fabrication methods; however, their lightweight advantage is partly offset by large unit dimensions, resulting in a relatively high weight per unit area, particularly for wideband implementations. Similarly, Printed Circuit Board (PCB)-based absorptive FSSs [17], while offering broadband absorption, exhibit a substantially increased areal weight density due to their large footprint and multilayer configuration, leading to a total weight exceeding 500 g. More structurally complex designs, such as aluminum honeycomb cavity FSSs fabricated using

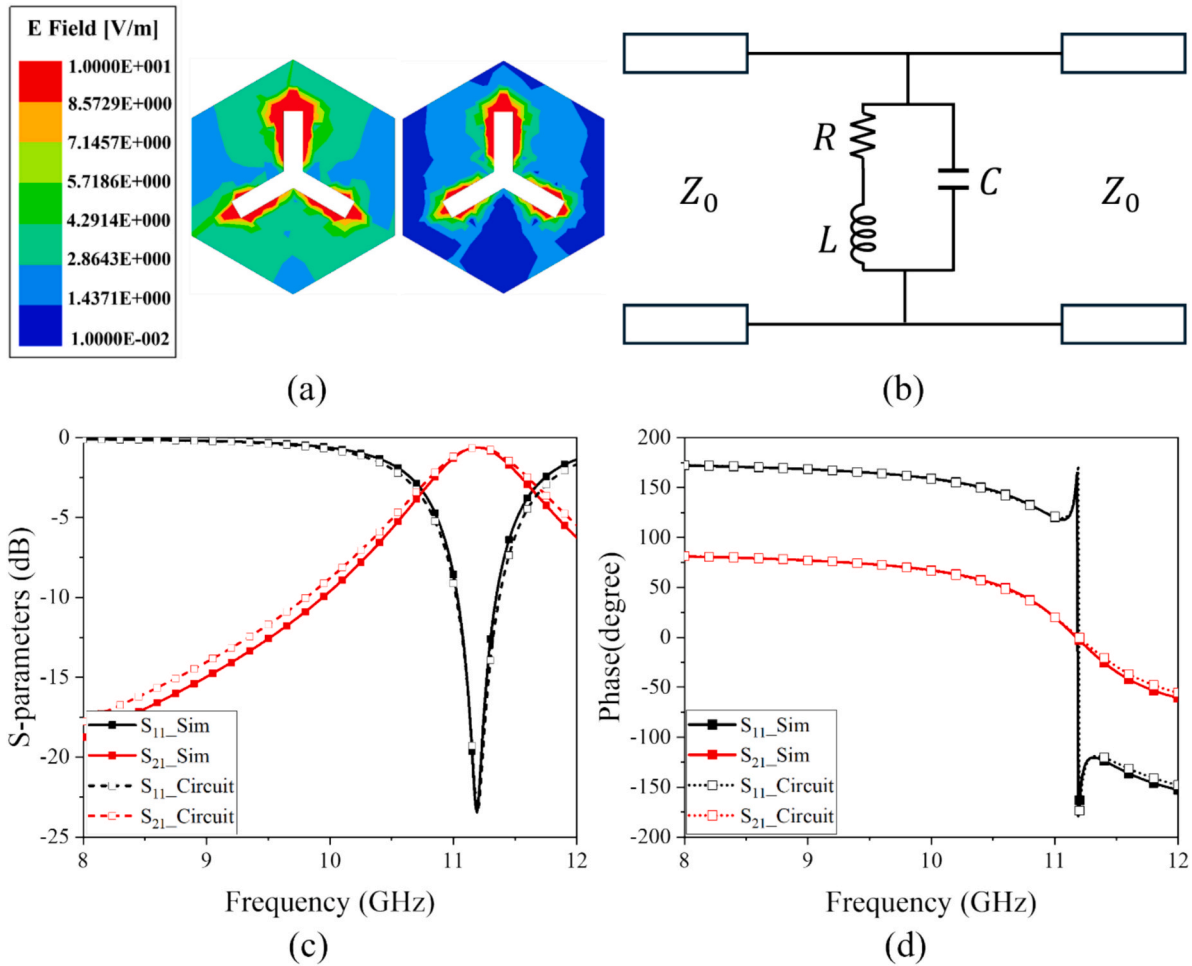


Fig. 15. (a) Simulated electromagnetic field distribution; (b) equivalent RLC circuit representation; (c) comparison between RLC circuit simulation and full-wave simulation results; and (d) comparison of simulation and RLC circuit phase response.

Table 1

Comparison between the proposed MXene-based frequency-selective surface (FSS) and previously reported lightweight frequency-selective surfaces.

Ref.	Fss Type	Center frequency (GHz)	Total weight (g)	Fabrication process	Unit Size	Cost	Return loss (dB)	Insertion loss (dB)
[12]	Three-layer FSS	–	152.6	Screen/inkjet printing	204 × 204 mm ²	Low	< 10	≈ 0
[13]	Aramid Honeycomb FSS	7	49.7 (2nd-order FSS)52.1 (wideband FSS)	Silver + Paper	300 × 300 mm ²	Low	≈ 0	≤ 20
[17]	Absorptive FSS	9.95	534	PCB	300 × 300 mm ²	High	< 10	≈ 0
[18]	Aluminum Honeycomb Cavity FSS	7.07	169.3	PCB + CNC	310 × 310 mm ²	High	< 15	0.3–0.9
[35]	3D conformal FSS	~33	–	Copper Electroplating	Diameter 80 mm ²	High	< 10	~1
This work	MXene coated FSS	11.2	28.3	MXene + Dip coating	114.3 × 114 mm²	Low	21	0.74

combined PCB and Computer Numerical Control (CNC) processes [18], achieve low insertion loss (0.3–0.9 dB) but at the expense of high fabrication cost and increased weight relative to their physical size (169.3 g). Likewise, 3D conformal FSSs realized via copper electroplating [35] demonstrate angularly stable transmission around 33 GHz, yet their areal weight density and fabrication complexity remain relatively high due to the metallization process. In contrast, the proposed MXene-coated FSS achieves a strong return loss of 21 dB and a low insertion loss of 0.74 dB at 11.2 GHz, while maintaining a significantly reduced weight relative to its footprint, with a total weight of only 28.3 g

for a unit size of 114.3 × 114 mm². This results in a markedly lower area-normalized weight compared to previously reported designs, despite being fabricated using a low-cost process based on 3D printing and solution-based MXene dip coating, without relying on PCB processing, CNC machining, or copper electroplating. Overall, the comparison in Table 1 indicates that the proposed approach offers a more favorable weight-to-size ratio, together with competitive electromagnetic performance and low fabrication cost, highlighting its suitability for lightweight and scalable FSS applications.

3. Conclusion

This study presents a novel fabrication approach for FSSs by combining stereolithographic (SLA) 3D printing with a dip-coating process using conductive $\text{Ti}_3\text{C}_2\text{T}_x$ MXene. The proposed method facilitates rapid and scalable production of structurally complex FSS designs, without relying on traditional photolithography or vacuum deposition techniques. By harnessing the solution-processable nature of MXene and the geometric versatility of SLA printing, we successfully fabricated a hexagonal Y-slot bandpass FSS structure exhibiting high structural fidelity and excellent conductivity. A key advantage of this approach is its lightweight characteristic. The MXene-coated FSS showed a 99% reduction in coating weight compared to a copper-taped equivalent, with only a minimal 0.1 g increase over the bare substrate—highlighting the negligible material load introduced by the dip-coating process. This renders the proposed structure especially suitable for aerospace, satellite, and other weight-sensitive electromagnetic applications. Electromagnetic characterisation demonstrated that the fabricated FSS maintained excellent performance, featuring a resonant frequency of 11.2 GHz, an insertion loss of 0.743 dB, and a return loss of 21.1 dB. Moreover, the MXene coating exhibited environmental stability over 30 days with no significant degradation in sheet resistance, confirming the reliability and durability of the proposed fabrication process. Overall, the integration of MXene dip-coating with SLA printing offers a cost-effective, conformal, and lightweight solution for next-generation electromagnetic structures. Future work will explore multilayer MXene coatings, integration with flexible or foldable substrates, and extension to higher-frequency regimes.

4. Experimental

4.1. Materials

The Ti_3AlC_2 MAX phase (99.9% purity) was obtained from INNOMXENE Co., Ltd., Republic of Korea. Lithium fluoride (LiF, 98.5%) was purchased from Alfa Aesar, while hydrochloric acid (HCl, 37%), and hydrofluoric acid (HF, ACS reagent grade, 48%), were procured from Sigma-Aldrich. All chemicals were used without further purification.

4.2. $\text{Ti}_3\text{C}_2\text{T}_x$ MXene synthesis

The $\text{Ti}_3\text{C}_2\text{T}_x$ MXene was synthesized by selectively etching aluminum from the Ti_3AlC_2 MAX phase using a modified minimally intensive layer delamination (MILD) method. In a typical synthesis, 1 g of Ti_3AlC_2 powder was slowly added to a solution containing 1.6 g of LiF dissolved in 20 mL of 9 M HCl and 3 mL of aqueous HF in a polypropylene bottle under continuous stirring. The mixture was stirred at 35 °C for 24 h to ensure complete etching of the Al layers. After etching, the resulting mixture was washed repeatedly with deionized water by centrifuged at 5000 rpm for 7 min until the pH of the supernatant reached approximately 6. To separate single-layer MXene flakes, the dispersion was further centrifuged at 3500 rpm for 5 min, allowing sedimentation of unexfoliated particles. The resulting supernatant, containing single layered $\text{Ti}_3\text{C}_2\text{T}_x$ MXene was collected for further characterization and coating.

CRediT authorship contribution statement

Jewon Woo: Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Conceptualization. **Junghyeon Kim:** Validation, Methodology, Conceptualization. **Sooyeong Cho:** Validation, Methodology. **Tufail Hassan:** Visualization, Validation, Methodology. **Chong Min Koo:** Writing – review & editing, Funding acquisition. **Sungjoon Lim:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Sungjoon Lim reports financial support was provided by National Research Foundation of Korea. Sungjoon Lim reports financial support was provided by Institute of Information & Communications Technology Planning. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

References

- [1] K. Sarabandi, N. Behdad, A Frequency Selective Surface with Miniaturized elements, *IEEE Trans. Antennas Propag.* 55 (2007) 1239–1245, <https://doi.org/10.1109/TAP.2007.895567>.
- [2] R. Phon, S. Ghosh, S. Lim, Novel Multifunctional Reconfigurable active Frequency Selective Surface, *IEEE Trans. Antennas Propag.* 67 (2019) 1709–1718, <https://doi.org/10.1109/TAP.2018.2889002>.
- [3] C.L. Valle, G.T. Carranza, R.C. Rumpf, Conformal Frequency Selective Surfaces for Arbitrary Curvature, *IEEE Trans. Antennas Propag.* 71 (2023) 612–620, <https://doi.org/10.1109/TAP.2022.3216960>.
- [4] J. Yang, H. Zheng, Y. Pang, B. Qu, Y. Li, J. Wang, Z. Xu, Design, modelling, and manufacturing of sandwich radome structure with out-of-band absorption and in-band transmission performances, *Compos. Struct.* 339 (2024), <https://doi.org/10.1016/j.compstruct.2024.118138>.
- [5] C. Wang, H. Lei, Y. Huang, H. Li, M. Chen, D. Fang, Effects of stitch on mechanical and microwave absorption properties of radar absorbing structure, *Compos. Struct.* 195 (2018) 297–307, <https://doi.org/10.1016/j.compstruct.2018.04.077>.
- [6] L. Zheng, L. Niu, T. Wang, X. Li, X. Wang, R. Gong, Integrated lightweight gradient honeycomb metastructure with microwave absorption and mechanical properties: Analysis, design, and verification, *Compos. Struct.* 305 (2023), <https://doi.org/10.1016/j.compstruct.2022.116464>.
- [7] H. Rafiepour, A.R. Setoodeh, A. Kin-Tak Lau, Mechanical and electromagnetic behavior of fabricated hybrid composite sandwich radome with a new optimized frequency-selective surface, *Compos. Struct.* 273 (2021), <https://doi.org/10.1016/j.compstruct.2021.114256>.
- [8] H. Lu, S. Yang, J. Jin, G. Li, Design, simulation and manufacture of a flexible frequency selective surface based on aramid/carbon fiber woven fabric, *Mater. Des.* 245 (2024), <https://doi.org/10.1016/j.matdes.2024.113282>.
- [9] J. Kim, P. Jepiti, M. Lee, E. Park, R. Phon, S. Lim, Screen-printing high/low resistance using only a single silver nanowire ink: Resistance-gradient metasurface application for broadband microwave absorption and optical transparency, *Mater. Des.* 247 (2024), <https://doi.org/10.1016/j.matdes.2024.113451>.
- [10] A. Gouda, S. Ghosh, Double-Curved Conformal Bandpass Frequency Selective Surface for Radome applications, *IEEE Trans. Antennas Propag.* 73 (2025) 4488–4497, <https://doi.org/10.1109/TAP.2025.3552218>.
- [11] Y. Han, T. Liu, Q. Li, W. Che, Q. Xue, A Bandpass Frequency-Selective Surface based on an Aramid-Paper Honeycomb Sandwich Structure, *IEEE Trans. Antennas Propag.* 72 (2024) 1039–1044, <https://doi.org/10.1109/TAP.2023.3326655>.
- [12] T. Wang, S.J. Kuang, P.J. Qian, Y.L. Yan, J. Hu, Y. Li, J.B. Mao, Organic UWB metamaterial absorber with angle insensitive based on flexible frequency selective surface, *Opt. Mater. (Amst.)* 157 (2024), <https://doi.org/10.1016/j.optmat.2024.116121>.
- [13] Y. Han, S. Liao, X. Xiu, B. Li, Y. Chang, Q. Xue, W. Che, Bandstop frequency selective surfaces based on aramid paper honeycomb structure, *IEEE Trans. Antennas Propag.* 70 (2022) 8164–8172, <https://doi.org/10.1109/TAP.2022.3164209>.
- [14] R.S. Anwar, L. Mao, H. Ning, Frequency Selective Surfaces: a Review, *Applied Sciences (Switzerland)* 8 (2018), <https://doi.org/10.3390/app8091689>.
- [15] A. Lalbakhsh, M.U. Afzal, K.P. Esselle, S.L. Smith, All-Metal Wideband Frequency-Selective Surface Bandpass Filter for TE and TM Polarizations, *IEEE Trans. Antennas Propag.* 70 (2022) 2790–2800, <https://doi.org/10.1109/TAP.2021.3138256>.

- [16] P.C. Zhao, Z.Y. Zong, W. Wu, B. Li, D.G. Fang, Miniaturized-Element Bandpass FSS by Loading Capacitive Structures, *IEEE Trans. Antennas Propag.* 67 (2019) 3539–3544, <https://doi.org/10.1109/TAP.2019.2902633>.
- [17] Y. Chen, W. Yu, Y. Du, X.H. Zhang, L. Liu, G.Q. Luo, Low-Profile Broadband Absorptive Frequency-Selective Surface based on Resistor-Loaded Bandpass FSS, *IEEE Trans. Antennas Propag.* 73 (2025) 7741–7751, <https://doi.org/10.1109/TAP.2025.3581399>.
- [18] N. Li, Y. Jiang, Y. Han, Investigation on Bandpass Frequency Selective Surface based on Aluminum Honeycomb Cavity, *IEEE Antennas Wirel. Propag. Lett.* 24 (2025) 3263–3267, <https://doi.org/10.1109/LAWP.2025.3587792>.
- [19] S. Ghosh, S. Lim, A Miniaturized Bandpass Frequency Selective Surface Exploiting Three-Dimensional Printing Technique, *IEEE Antennas Wirel. Propag. Lett.* 18 (2019) 1322–1326, <https://doi.org/10.1109/LAWP.2019.2915048>.
- [20] S. Qiu, Q. Guo, Z. Li, Tunable Frequency Selective Surface based on a Sliding 3D-printed Inserted Dielectric, *IEEE Access* 9 (2021) 19743–19748, <https://doi.org/10.1109/ACCESS.2021.3054434>.
- [21] H. Jeong, E. Park, S. Lim, Three-Dimensional Printed and Fluidic Dielectric Material Optically Transparent Metasurface for Switchable Absorption and Reflection Functionality in Microwave Frequency Region, *Waves Random Complex Media* (2022), <https://doi.org/10.1080/17455030.2022.2058712>.
- [22] S. Ghosh, S. Lim, Perforated Lightweight Broadband Metamaterial Absorber based on 3-D Printed Honeycomb, *IEEE Antennas Wirel. Propag. Lett.* 17 (2018) 2379–2383, <https://doi.org/10.1109/LAWP.2018.2876023>.
- [23] K. Kim, Y. Kim, E. Park, H. Jeong, S. Lim, Frequency- and Bandwidth-Controllable Electromagnetic Absorber using 3D-printed Shape memory Meta-Wires, *Virtual Phys. Prototyp.* 19 (2024), <https://doi.org/10.1080/17452759.2024.2351143>.
- [24] Y. Kim, D.A. Pham, R. Phon, S. Lim, Lightweight 3D-printed Fractal Gradient-Index Lens Antenna with Stable Gain Performance, *Fractal and Fractional* 6 (2022), <https://doi.org/10.3390/fractalfract6100551>.
- [25] S. Chakraborty, M.C. Biswas, 3D printing technology of polymer-fiber composites in textile and fashion industry: a potential roadmap of concept to consumer, *Compos. Struct.* 248 (2020), <https://doi.org/10.1016/j.compstruct.2020.112562>.
- [26] D. Wang, R. Wang, S. Chen, J. Gao, C. Cai, Y. Zheng, X. Liu, B. Qu, N. Chen, D. Zhuo, Low viscosity and highly flexible stereolithographic 3D printing resins for flexible sensors, *Mater. Des.* 243 (2024), <https://doi.org/10.1016/j.matdes.2024.113052>.
- [27] T.D. Ngo, A. Kashani, G. Imbalzano, K.T.Q. Nguyen, D. Hui, Additive Manufacturing (3D printing): a Review of Materials, Methods, applications and challenges, *Compos. B Eng.* 143 (2018) 172–196, <https://doi.org/10.1016/j.compositesb.2018.02.012>.
- [28] S.C. Joshi, A.A. Sheikh, 3D Printing in Aerospace and its Long-Term Sustainability, *Virtual Phys. Prototyp.* 10 (2015) 175–185, <https://doi.org/10.1080/17452759.2015.1111519>.
- [29] A. Bigham, A. Zarepour, A. Khosravi, S. Irvani, A. Zarrabi, 3D and 4D Printing of MXene-based Composites: from Fundamentals to Emerging applications, *Mater. Rev.* (2024), <https://doi.org/10.1039/d4mh01056f>.
- [30] G.D. Goh, K.K. Wong, N. Tan, H.L. Seet, M.L.S. Nai, Large-Format Additive Manufacturing of Polymers: a Review of Fabrication Processes, Materials, and Design, *Virtual Phys. Prototyp.* 19 (2024), <https://doi.org/10.1080/17452759.2024.2336160>.
- [31] N. Shahrubudin, T.C. Lee, R. Ramlan, An Overview on 3D Printing Technology: Technological, Materials, and Applications, in: *Procedia Manuf.*, Elsevier B.V., 2019; pp. 1286–1296. doi: 10.1016/j.promfg.2019.06.089.
- [32] J.B. Roca, P. Vaishnav, E.R.H. Fuchs, M.G. Morgan, Policy Needed for Additive Manufacturing, *Nat. Mater.* 15 (2016) 815–818, <https://doi.org/10.1038/nmat4658>.
- [33] J. Gardan, Smart Materials in Additive Manufacturing: State of the Art and Trends, *Virtual Phys. Prototyp.* 14 (2019) 1–18, <https://doi.org/10.1080/17452759.2018.1518016>.
- [34] I.M. Alarifi, Revolutionising Fabrication advances and applications of 3D Printing with Composite Materials: a Review, *Virtual Phys. Prototyp.* 19 (2024), <https://doi.org/10.1080/17452759.2024.2390504>.
- [35] H.F. Álvarez, D.A. Cadman, A. Goulas, M.E. de Cos Gómez, D.S. Engström, J. C. Vardaxoglou, S. Zhang, 3D Conformal Bandpass Millimeter-Wave Frequency Selective Surface with improved Fields of View, *Sci. Rep.* 11 (2021), <https://doi.org/10.1038/s41598-021-91218-y>.
- [36] Y. Gogotsi, B. Anasori, The rise of MXenes, *ACS Nano* 13 (2019) 8491–8494, <https://doi.org/10.1021/acsnano.9b06394>.
- [37] B. Akuzum, K. Maleski, B. Anasori, P. Lelyukh, N.J. Alvarez, E.C. Kumbur, Y. Gogotsi, Rheological Characteristics of 2D Titanium Carbide (MXene) Dispersions: a Guide for Processing MXenes, *ACS Nano* 12 (2018) 2685–2694, <https://doi.org/10.1021/acsnano.7b08889>.
- [38] V. Orts Mercadillo, K.C. Chan, M. Caironi, A. Athanassiou, I.A. Kinloch, M. Bissett, P. Cataldi, Electrically Conductive 2D Material Coatings for flexible and Stretchable Electronics: a Comparative Review of Graphenes and MXenes, *Adv. Funct. Mater.* 32 (2022), <https://doi.org/10.1002/adfm.202204772>.
- [39] V. Kedambaimoole, K. Harsh, K. Rajanna, P. Sen, M.M. Nayak, S. Kumar, MXene Wearables: Properties, Fabrication strategies, Sensing Mechanism and applications, *Mater. Adv.* (2022), <https://doi.org/10.1039/d1ma01170g>.
- [40] K. Xie, J. Wang, S. Xu, W. Hao, L. Zhao, L. Huang, Z. Wei, Application of Two-Dimensional MXene materials in sensors, *Mater. Des.* 228 (2023), <https://doi.org/10.1016/j.matdes.2023.111867>.
- [41] A. Iqbal, J. Kwon, T. Hassan, S.W. Park, W.H. Lee, J.M. Oh, J. Hong, J. Lee, S. M. Naqvi, U. Zafar, S.J. Kim, J.H. Park, M.K. Kim, C.M. Koo, Environmentally Stable and Highly Crystalline MXenes for Multispectral Electromagnetic Shielding up to Millimeter Waves, *Adv. Funct. Mater.* (2024), <https://doi.org/10.1002/adfm.202409346>.
- [42] O. Niksan, L. Bi, K.K. Kazemi, R. Rakhmanov, Y. Gogotsi, M.H. Zarifi, MXene Guides Microwaves through 3D Polymeric Structures, *Mater. Today* 73 (2024) 47–55, <https://doi.org/10.1016/j.mattod.2023.12.013>.
- [43] C. Li, G. Wang, M. Peng, C. Liu, T. Feng, Y. Wang, F. Qin, Reconfigurable Origami/Kirigami Metamaterial Absorbers developed by Fast Inverse Design and Low-Concentration MXene Inks, *ACS Appl. Mater. Interfaces* 16 (2024) 42448–42460, <https://doi.org/10.1021/acsaami.4c07084>.
- [44] O. Niksan, L. Bi, Y. Gogotsi, M.H. Zarifi, MXene-Based Kirigami designs: Showcasing Reconfigurable Frequency Selectivity in Microwave Regime, *Nat. Commun.* 15 (2024), <https://doi.org/10.1038/s41467-024-51853-1>.
- [45] M.L. Matias, C. Pereira, H.V. Almeida, S. Jana, S. Panigrahi, U.D. Menda, D. Nunes, E. Fortunato, R. Martins, S. Nandy, 3D Printed MXene Architectures for a Plethora of Smart applications, *Mater. Today Adv.* 23 (2024), <https://doi.org/10.1016/j.mtdadv.2024.100512>.
- [46] M. Han, Y. Liu, R. Rakhmanov, C. Israel, M.A.S. Tajin, G. Friedman, V. Volman, A. Hoorfar, K.R. Dandekar, Y. Gogotsi, Solution-Processed Ti3C2Tx MXene Antennas for Radio-Frequency Communication, *Adv. Mater.* 33 (2021), <https://doi.org/10.1002/adma.202003225>.
- [47] Q. Wang, Y. Liu, E. Su, X. Su, Influence of reducing agent concentration on properties of flexible microwave absorbing coating containing silver coated FeSiAl powders, *Mater. Today Nano* 29 (2025), <https://doi.org/10.1016/j.mtnano.2025.100603>.
- [48] Q. Wang, Y. Liu, Y. Ma, E. Su, X. Su, Preparation and electromagnetic property of Ag@FeSiAl/polyurethane resin flexible absorption wave coating, *J. Alloys Compd.* 1021 (2025), <https://doi.org/10.1016/j.jallcom.2025.179666>.
- [49] Q. Wang, X. Su, Y. Jia, Y. Liu, F. Shahzad, Regulation of Microstructure and Absorption Properties of MXene Materials: Theoretical and Experimental, *Adv. Sci.* 12 (2025), <https://doi.org/10.1002/adv.202509994>.
- [50] M. Alhabeib, K. Maleski, B. Anasori, P. Lelyukh, L. Clark, S. Sin, Y. Gogotsi, Guidelines for Synthesis and Processing of Two-Dimensional Titanium Carbide (Ti3C2Tx MXene), *Chem. Mater.* 29 (2017) 7633–7644, <https://doi.org/10.1021/acs.chemmater.7b02847>.
- [51] T. Hassan, A. Iqbal, B. Yoo, J.Y. Jo, N. Cakmakci, S.M. Naqvi, H. Kim, S. Jung, N. Hussain, U. Zafar, S.Y. Cho, S. Jeong, J. Kim, J.M. Oh, S. Park, Y. Jeong, C. M. Koo, Multifunctional MXene/Carbon Nanotube Janus Film for Electromagnetic Shielding and Infrared Shielding/Detection in Harsh Environments, *Nanomicro Lett.* 16 (2024), <https://doi.org/10.1007/s40820-024-01431-3>.
- [52] S. Doo, A. Chae, D. Kim, T. Oh, T.Y. Ko, S.J. Kim, D.Y. Koh, C.M. Koo, Mechanism and Kinetics of Oxidation Reaction of Aqueous Ti3C2Tx Suspensions at different pHs and Temperatures, *ACS Appl. Mater. Interfaces* 13 (2021) 22855–22865, <https://doi.org/10.1021/acsaami.1c04663>.
- [53] P. Verding, R. Mary Joy, D. Reenaers, R.S.N. Kumar, R. Rouzbahani, E. Jeunen, S. Thomas, D. Desta, H.G. Boyen, P. Pobedinskas, K. Haenen, W. Deferme, The Influence of UV-Ozone, O2 Plasma, and CF4 Plasma Treatment on the Droplet-based Deposition of Diamond Nanoparticles, *ACS Appl. Mater. Interfaces* 16 (2024) 1719–1726, <https://doi.org/10.1021/acsaami.3c14014>.
- [54] M. Sybakova, A. Hagemann, D. Rho, S. Kim, Review: 3-Aminopropyltriethoxysilane (APTES) Deposition Methods on Oxide Surfaces in solution and Vapor Phases for Biosensing applications, *Biosensors (Basel)* 13 (2023), <https://doi.org/10.3390/bios13010036>.
- [55] S. Wan, X. Li, Y. Chen, N. Liu, Y. Du, S. Dou, L. Jiang, Q. Cheng, High-strength scalable MXene films through bridging-induced densification, *Science* 374 (2021) 96–99, <https://doi.org/10.1126/science.abg2026>.
- [56] R. Cheng, B. Wang, J. Zeng, J. Li, J. Xu, W. Gao, K. Chen, Janus-inspired flexible cellulose nanofiber-assisted MXene/Silver nanowire papers with fascinating mechanical properties for efficient electromagnetic interference shielding, *Carbon* N. Y. 202 (2023) 314–324, <https://doi.org/10.1016/j.carbon.2022.10.079>.