

MetaVenom: Field Programmable Fully Passive Metasurfaces

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Abstract

Emerging high frequency wireless sensing and communication systems often leverage metasurfaces to modulate the signal propagation, thereby transcending Snell's law. Yet, existing metasurfaces are either active, which is constantly sustained by electrical power, or passive, which cannot be reconfigured. In this paper, we explore a quasi-dynamic metasurface using electrically morphable ferrofluid that enables a new category of metasurface design for wireless sensing and communication. We first characterize how ferrofluid material interact with high-frequency millimeter-wave signals. Next, we present a practical fabrication method of quasi-dynamic metasurface using thermoplastic 3D printing. We then develop a model to effectively manipulate the wireless signal propagation using an array of field-programmable ferrofluid cells. Our extensive evaluation results reveal the capabilities of a novel quasi-dynamic metasurface as an alternative to existing wireless tags for joint radar communication, and beamforming metasurfaces for enhancing millimeter-wave network coverage.

CCS Concepts

• Computer systems organization → Embedded and cyber-physical systems.

Keywords

5G, 6G, Metasurface, mmWave Sensing, IoT, 3D Printing

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1 Introduction

The transition from 5G to 6G and beyond is highly dependent on high frequency spectrum, such as the millimeter wave (mmWave) bands [14, 15, 36], which offer abundant band-

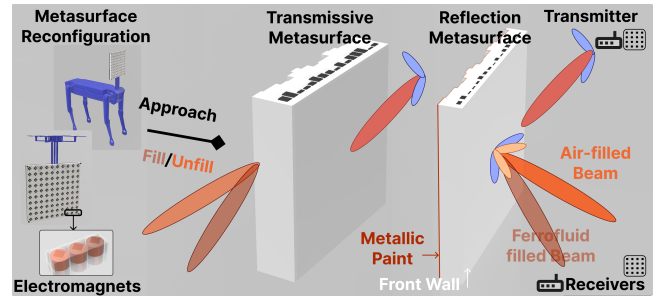


Figure 1: MetaVenom presents a quasi-dynamic RF metasurface with an independent reprogramming module that can be carried by a mobile device (e.g., drone, robot). Its unit cells comprise 3D printed thermoplastic and electromagnetically actuated ferrofluid to achieve arbitrary beam reconfiguration.

width for high-capacity communication. However, mmWave signals suffer from severe path loss, blockage, and sparse multipath propagation, making it difficult to provide robust coverage in practical environments. Metasurfaces, with their ability to manipulate electromagnetic waves in a highly efficient and customizable manner, present a promising solution to address these challenges. By engineering the phase response of sub-wavelength unit cells, metasurfaces can reshape radio propagation, enabling functionalities such as beam steering and coverage extension. Such an ability also enables novel joint communication and sensing use cases [33], which leverage the diverse metasurface-modulated signal patterns to convey information to radar devices.

Existing metasurface designs fall largely into two categories. Active metasurfaces [4, 6, 7, 11, 24, 26, 28, 56], also known as reconfigurable intelligent surfaces (RIS), integrate electronic components such as PIN diodes or varactors to dynamically adjust the phase response of individual unit cells. While these systems offer fine-grained programmability, they require continuous power supply, dedicated control circuitry, and often a separate wireless control channel. As a result, the overall hardware complexity approaches that of a full-fledged radio device, which significantly increases cost and deployment overhead. In contrast, fully passive metasurfaces [30, 38, 39, 44, 55] eliminate electronic components entirely, enabling extremely low-cost fabrication through PCB or 3D printing. These designs are attractive for large-area deployments but suffer from a fundamental limitation: their ability to reshape or redirect the RF signals is fixed at fabrication time. A manual replacement or redeployment of the metasurfaces is often needed when the coverage demand



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changes. This tension between reconfigurability and deployability raises a key question: *Can we achieve programmability for metasurfaces while retaining the simplicity and low cost of passive designs?*

In this paper, we propose MetaVenom, a new metasurface design that bridges this gap. The key idea is to *decouple the metasurface structure from its reconfiguration mechanism*. MetaVenom's metasurface, referred to as the ferrofluid-filled metasurface (FFMS), consists of an array of dielectric containers (i.e., unit-cell cavities), which can alter the phase responses of reflected mmWave signals. By selectively filling or removing ferrofluid from these cells, the metasurface can reshape the reflected wavefront and synthesize different beam patterns. A detachable external module, called the *FFMS Morpher*, uses controlled magnetic fields to transport ferrofluid within the metasurface, thereby reprogramming its beam pattern. This design enables a new class of quasi-dynamic passive metasurfaces that can be reprogrammed in the field using mobile platforms such as drones or robots. Unlike electronically controlled RIS with real-time beam pattern shift, MetaVenom is not intended for real-time channel tracking. Its approximately 20 s full-fill reconfiguration upper bound targets quasi-static deployments, such as scheduled crowd events, temporary outdoor coverage, and privacy or coverage configurations changed between operating periods. In these settings, a mobile FFMS Morpher can program a surface before service begins and then leave; the surface subsequently operates without standby power.

This MetaVenom design offers several advantages: **i)** Fully passive. The FFMS is standalone and will maintain its beam-shaping function when the FFMS Morpher reconfiguration module moves away. **ii)** Field reprogrammable. The FFMS can be reconfigured by the FFMS Morpher in a contactless manner, eliminating the need for mechanical changes such as reposition or replacement of the metasurfaces. **iii)** Low-cost. The entire metasurface can be fabricated at a fraction of the cost of active RIS systems using commodity 3D printing. The reconfiguration module is reusable by multiple metasurfaces across locations, and hence the cost can be amortized.

Realizing such salient features requires overcoming several fundamental challenges.

i) Designing and modeling multi-state ferrofluid unit cells. Conventional passive metasurfaces [30, 44, 55] rely on dielectric resonance structures whose resonant frequency and phase response are fixed at fabrication time, resulting in zero reconfigurability after deployment. Enabling reconfigurability while preserving a fully passive architecture requires a new design paradigm: each unit cell must support multiple distinct electromagnetic states without incorporating active electronics or power supply.

To achieve this capability, we design a multi-layer metasurface unit cell whose geometric structure determines the baseline phase response of reflected signals, while selectively filling the unit-cell cavity with ferrofluid shifts the resonant phase at the target frequency. We select an oil-based fer-

rofluid whose mmWave dielectric constant approximately matches that of common thermoplastics used in 3D printing. This material choice maximizes achievable phase shift while minimizing insertion loss caused by dielectric mismatch. However, precise high-frequency dielectric parameters for ferrofluids are typically unavailable from manufacturers. We overcome this challenge by first estimating the material properties using effective medium modeling and then refining them through empirical calibration. The resulting material characterization allows us to engineer the air-filled and ferrofluid-filled states of the unit cell, whose combination spans the phase space required for metasurface beam steering.

ii) Enabling contactless reconfiguration of passive metasurfaces. Achieving reconfigurability without embedded electronics requires a mechanism for modifying the metasurface state after deployment. However, manipulating ferrofluid within mmWave-scale unit cells is nontrivial. Conventional fluid control techniques rely on mechanical pumps or physical contact, which would negate the advantages of passive metasurfaces.

MetaVenom addresses this challenge through the FFMS Morpher, a detachable magnetic reconfiguration module. The FFMS Morpher uses an array of electromagnets to generate controlled magnetic fields that transport ferrofluid between reservoirs and unit-cell containers without direct contact. Sequential activation of electromagnets creates a moving magnetic field that pulls ferrofluid across the surface, enabling programmable filling patterns. We profile ferrofluid transfer volume against electromagnet power to refine fill-state control, and characterize the residual film left by fill/unfill cycles, showing its negligible impact on beam-forming gain. The surface retains its programmed beam once the FFMS Morpher is removed.

iii) Synthesizing diverse beam patterns under coarse-grained ferrofluid control. Magnetic actuation imposes a fundamental spatial mismatch. At mmWave frequencies, unit cells are small due to the short wavelength, yet moving ferrofluid demands comparatively large electromagnet coils. Per-unit-cell control is therefore infeasible, and reconfiguration must occur at coarser granularity. In the extreme, filling the entire surface with air or ferrofluid yields only two configurations.

MetaVenom addresses this limitation through an Array-of-Subarrays (AoSA) architecture combined with a hybrid optimization framework. We partition the metasurface into subarrays that can independently toggle between two material states (i.e., air-filled or ferrofluid-filled). We formulate beam synthesis as a joint optimization problem that determines phase distributions for both states and computes a bitmap specifying which subarrays should switch state for each target beam pattern. This allows MetaVenom to generate diverse beam patterns, including pencil, fan, and multi-arm beams, despite the coarse-grained magnetic actuation.

We prototype and evaluate MetaVenom through both controlled experiments and real-world deployments on a 60 GHz radio and radar testbed. Extensive experiments show MetaVenom reconfigures mmWave beams in both reflective and transmissive modes, switching among multiple patterns and steering energy toward desired directions. Beamforming performance matches existing passive metasurfaces while uniquely adding field programmability. We further explore MetaVenom’s use as a joint radar–communication (JRC) tag, where different ferrofluid filling patterns encode information detectable by FMCW radar. Experimental results show that each tag is clearly identifiable from its radar range profile, achieving at least 3-bit coding capacity. MetaVenom can be easily extended to other mmWave frequencies with similar ferrofluid infill requirements and cell size as our 60 GHz prototype. However, lower frequencies (e.g., sub-6 GHz) will lead to orders of magnitude larger cell, which is impractical. MetaVenom is open-sourced¹.

In summary, this paper makes the following contributions:

- We introduce a reconfigurable, liquid-filled phase-cell architecture that brings field programmability to an otherwise passive mmWave metasurface.
- We co-design a detachable magnetic programmer and a standalone surface, enabling contactless, zero-standby-power reconfiguration without embedding control electronics in each deployed surface.
- We develop an AoSA synthesis framework that maps ferrofluid bitmap to beams in reflective and transmissive configurations.
- We experimentally validate the AoSA beamforming and JRC tag at 60 GHz using fabricated prototypes.

2 Preliminaries

2.1 Ferrofluid mmWave Modeling

Prior RF ferrofluid models addressed microwave parameter extraction [52], bulk permittivity of magnetite composites [18], microwave-to-terahertz modulation [27, 54], and dried-ink amplitude patterns at mmWave frequencies [25]. They capture how much energy the fluid absorbs or reflects, rather than the phase it imparts. MetaVenom is the first to model the phase effect, deriving its per cell from Maxwell–Garnett permittivity and unit-cell geometry while keeping the fluid liquid and magnetically reprogrammable.

Let ϵ_m denote the dielectric constant of the carrier fluid and ϵ_i the dielectric constant of the suspended nanoparticles. If the nanoparticle volume fraction is V , the effective dielectric constant of the ferrofluid can be approximated using Maxwell–Garnett effective medium theory [8]: $\epsilon_{\text{eff}} = \epsilon_m \frac{\epsilon_i(1+2V)+2\epsilon_m(1-V)}{\epsilon_i(1-V)+\epsilon_m(2+V)}$. At 60 GHz, typical values are approximately $\epsilon_m \approx 2$ for hydrocarbon solvents [21] and $\epsilon_i \approx 18$ for magnetite nanoparticles [18]. For a ferrofluid synthesized [35] with roughly $V = 10\%$ nanoparticle surfactant volume fraction, the resulting effective dielectric constant is approx-

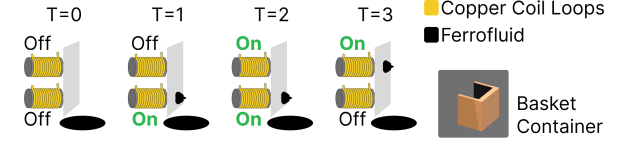


Figure 2: Electromagnets move ferrofluid against gravity in a four-step sequence, and a 3D-printed thermo-plastic basket retains it in position without power.

imately $\epsilon_{\text{eff}} \approx 3$. This value closely matches the permittivity of common thermoplastics used in 3D printing.

2.2 Electrical Actuation of Ferrofluid

To transport the ferrofluid across the metasurface without mechanical controllers, we use current-driven electromagnets [47]. Current flowing through a solenoid generates a magnetic field that manipulates ferrofluid when the magnetic force in the vertical direction exceeds gravity. The magnetic field strength generated by a solenoid can be approximated as [41] $B(d) \approx \frac{\mu_0 NI}{d}$, $F = V \chi \frac{\mu_0}{2} \nabla B^2$, where B is the magnetic field strength, I is the current, N is the number of turns of conductor coil, μ_0 is vacuum permeability, and d is the distance from the wire. F is the magnetic force generated from the electromagnet on the ferrofluid, V is the volume of ferrofluid, ∇B^2 indicates the gradient of magnetic field strength. Strong magnetic force requires close electromagnet proximity and high coil turn count. This limits small electromagnets from generating sufficient magnetic force to move ferrofluid in bulk. We present a workaround solution with our FFMS Morpher in Sec. 5. Fig. 2 shows electromagnet pairs lifting ferrofluid to desired surface positions via power-switching patterns. Magnetic actuation drives both vertical and lateral ferrofluid movement, enabling dynamic filling patterns for phase control and beam steering.

3 FFMS Design

FFMS comprises an array of unit cell cavities, designed to hold ferrofluid while causing phase shift to incidental waves. In this section, we first describe the electromagnetic behavior of the proposed ferrofluid unit cell, and then explain how these cells are configured to synthesize metasurface beam patterns based on the array-of-subarrays (AoSA) architecture.

3.1 Unit Cell Design

As illustrated in Fig. 3(a) and (e), each unit cell consists of four components: the *front wall* that interacts with the incident wave; the *PLA cuboid* that determines the baseline (air-filled) phase shift pattern; the *ferrofluid container* that changes the phase shift when filled by ferrofluid; and the *conductive paint* acting as common ground for the reflective metasurface.

3.1.1 Unit Cell Phase Control. FFMS induces phase delays via dielectric thickness variations, as materials with higher dielectric constants slow RF wave propagation more strongly [42]. By arranging unit cells with different phase responses,

¹https://github.com/baichengchen/MetaVenom_MobiCom2026

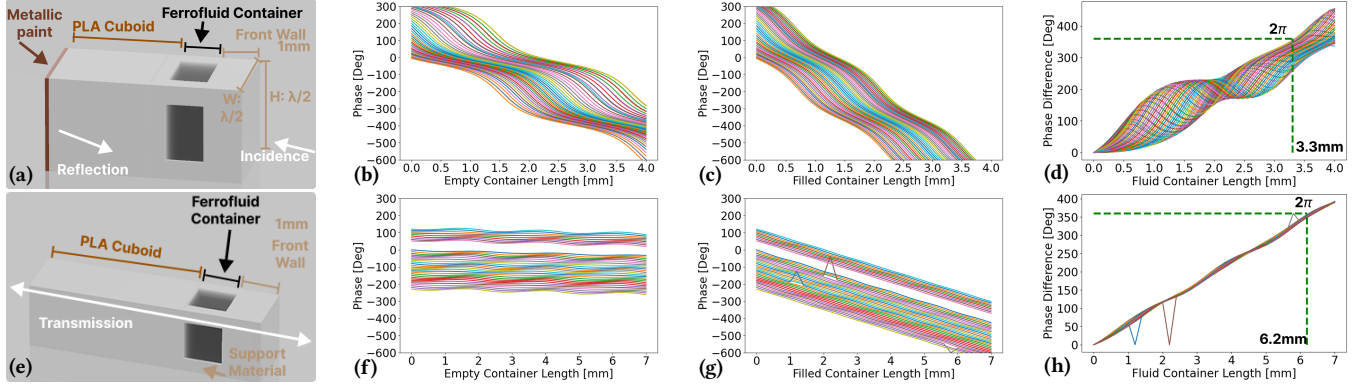


Figure 3: (a) Reflective unit cell causes phase delay with front wall, ferrofluid container, and PLA block. (b) and (c) are empty and ferrofluid filled container length (CL) from 0 to 4 mm. Colored lines in (b) and (c) is PLA from 0.5 to 4 mm. (d) = (b)-(c). At PLA=0.5 mm and CL=3.3 mm, ferrofluid achieves 2π phase reconfigurability. (e) Transmissive model. (f) and (g) are empty and ferrofluid filled CL from 0 to 7 mm. Colored lines in (f) and (g) are PLA block lengths varying from 8 to 15 mm. (h) = (f)-(g). 2π requires PLA=8 mm and CL=6.2 mm for transmissive model.

the metasurface steers beams in the desired direction through coherent signal combination.

To characterize the newly designed unit cell electromagnetic, we perform full-wave simulations with Floquet port analysis in HFSS [2]. This approach models an infinite periodic array and extracts the phase delay contributed by each material layer within the unit cell.

As shown in Fig. 3(a), the phase response of the half-wavelength cuboid unit cell is primarily determined by two geometric parameters: the ferrofluid container length (CL) and the PLA cuboid thickness. When the cavity is air-filled, the phase response follows the profile shown in Fig. 3(b). When the cavity is filled with ferrofluid, the higher dielectric constant increases the electrical path length, steepening the phase shift slope as illustrated in Fig. 3(c). By varying the geometric parameters, specifically the PLA thickness and ferrofluid container length, we obtain a full 2π phase range for the air-filled state, and an additional 2π phase range when ferrofluid is present, as shown in Fig. 3(d). A similar analysis for transmissive metasurface configurations is shown in Fig. 3(e)–(h). These results demonstrate that *the geometrical parameters combined with ferrofluid infill states effectively modify the electromagnetic properties of the unit cell, enabling programmable phase control.*

3.1.2 Geometric Quantization of Unit Cell. AoSA fabrication requires each unit cell to satisfy phase requirements for both air-filled and ferrofluid-filled states, subject to geometric quantization imposed by the minimum 3D printer step size.

$$(h_{\text{PLA}}, h_{\text{CL}})_{x,y} = \arg \min_{h_{\text{PLA}}, h_{\text{CL}}} \left[\left| \Psi_{x,y}^{\text{air}} - \mathcal{L}(h_{\text{PLA}}, h_{\text{CL}}) \right| + \left| \Psi_{x,y}^{\text{FF}} - \mathcal{L}(h_{\text{PLA}}, h_{\text{CL}}) \right| \right] \quad (1)$$

We select the optimal PLA block thickness h_{PLA} and ferrofluid container length h_{CL} by minimizing the combined phase error using a lookup table $\mathcal{L}$ from full wave simulation. $\Psi_{x,y}^{\text{air}}$ and $\Psi_{x,y}^{\text{FF}}$ denote the target phase shifts at position (x, y)

for the air-filled and ferrofluid-filled states, respectively. As illustrated in Fig. 3, the unit cell phases wraps around 2π , so the optimization is conducted over the full wrapped phase space. The resulting $(h_{\text{PLA}}, h_{\text{CL}})_{x,y}$ yields a fabrication-ready design that jointly satisfies both beam pattern requirements.

3.1.3 Incident Angle Distortion. The phase profiles in Fig. 3 assume normal incidence. However, when waves impinge at oblique angles, the effective propagation distance within each unit cell increases, introducing additional phase offsets. As shown in Fig. 6(a), both air-filled and ferrofluid-filled configurations exhibit angle-dependent phase offsets due to the increased path length at oblique incidence. These offsets can reach 100° with just 20° incidence, which can significantly distort the radiated beam pattern. As demonstrated on the right side of Fig. 6(a), failure to account for this effect results in aberrations that substantially reduce the main lobe gain and introduce unwanted scattering.

To compensate for this angle-dependent phase response, we expand our lookup table to $\mathcal{L}(h_{\text{PLA}}, h_{\text{CL}}, k_{\text{inc}})$, and the resulting phased array to fabrication parameter mapping is updated as follows:

$$(h_{\text{PLA}}, h_{\text{CL}})_{x,y} = \arg \min_{h_{\text{PLA}}, h_{\text{CL}}} \left[\left| \Psi_{x,y}^{\text{air}} - \mathcal{L}(h_{\text{PLA}}, h_{\text{CL}}, k_{\text{inc}}) \right| + \left| \Psi_{x,y}^{\text{FF}} - \mathcal{L}(h_{\text{PLA}}, h_{\text{CL}}, k_{\text{inc}}) \right| \right] \quad (2)$$

This correction allows the fabricated metasurface to maintain accurate beam steering even under oblique incidence.

3.1.4 Expanding the Field of View. Existing metasurface designs typically employ flat front-wall geometries, which concentrate reflected energy near boresight and suffer from diminishing radiation efficiency at wide angles [30, 44, 55]. To explore potential improvements, we evaluate several alternative unit-cell front-wall geometries. Specifically, we model three geometries that occupy the unit cell's square footprint: cuboid, spherical, and triangular facets. For each geometry, we simulate the radiation pattern of a single unit

cell in HFSS and measure the resulting energy distribution across azimuth and elevation angles. In simulation, the radiation source is placed at the conductive paint layer to emulate reflection from the metasurface.

As shown in Fig. 4, cuboid facets produce a relatively uniform main lobe within $\pm 45^\circ$, spherical facets distribute energy more evenly across $\pm 85^\circ$, and triangular facets generate grating lobes that favor wide-angle reflections. Given these tradeoffs, we adopt the flat front-wall geometry as the default design to concentrate energy within $\pm 45^\circ$.

3.2 Creating Reconfigurable Beam Patterns through AoSA

In the AoSA architecture, neighboring unit cells form a subarray that shares a common filling state, giving each subarray two electromagnetic configurations: air-filled or ferrofluid-filled. This section describes how MetaVenom synthesizes beam patterns under this binary control constraint.

3.2.1 From Phase Shifts to Beam Patterns. The far-field radiation pattern of the AoSA metasurface is determined by two coupled factors: the continuous phase shift assigned to each unit cell and the binary filling state of each subarray.

For a target reflection direction $(\theta_{\text{ref}}, \phi_{\text{ref}})$ under an incident direction $(\theta_{\text{inc}}, \phi_{\text{inc}})$, the ideal phase shift at unit cell (x, y) is given by the generalized reflection law [43]:

$$\Psi(x, y) = \frac{2\pi}{\lambda} [(\sin \theta_{\text{ref}} \cos \phi_{\text{ref}} - \sin \theta_{\text{inc}} \cos \phi_{\text{inc}})x + (\sin \theta_{\text{ref}} \sin \phi_{\text{ref}} - \sin \theta_{\text{inc}} \sin \phi_{\text{inc}})y]. \quad (3)$$

Here, $\sin \theta \cos \phi$ and $\sin \theta \sin \phi$ are phase delays along x - and y -directions. Unit cells imparting $\Psi(x, y)$ steer reflected signals constructively toward the target.

In the AoSA architecture, each subarray selects between two discrete phase states corresponding to air-filled and ferrofluid-filled states. The resulting phase profile therefore depends on both the fabricated unit cell geometry and the binary filling-state bitmap $\mathbf{b} \in \{0, 1\}^{N_s}$ across the N_s subarrays.

3.2.2 AoSA Phased Array Optimization. Since unit cell geometries are fixed after fabrication, the only runtime degree of freedom is the bitmap $\mathbf{b}$. To support arbitrary post-fabrication steering, we pre-optimize two global phase distributions Ψ^{air} and Ψ^{FF} corresponding to the air-filled and ferrofluid-filled states. For any desired steering angle, the optimal bitmap is then determined by selecting the filling state that minimizes phase error at each subarray:

$$b_i = \arg \min_{s \in \{\text{air}, \text{FF}\}} |\Psi_i(x, y) - \Psi_i^s|, \quad (4)$$

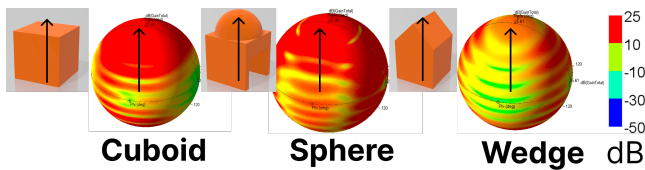


Figure 4: Unit cell radiation pattern. Energy scatters outward from center of the sphere.

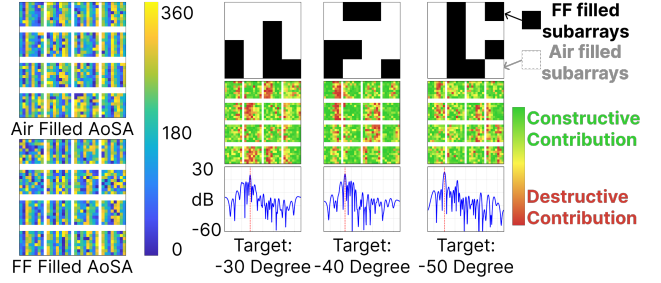


Figure 5: Genetic algorithm synthesized phased subarray contributions to targeted angle being optimized over multiple generations. (Codebook size=3; subarray with 8 elements each, and 4 subarrays).

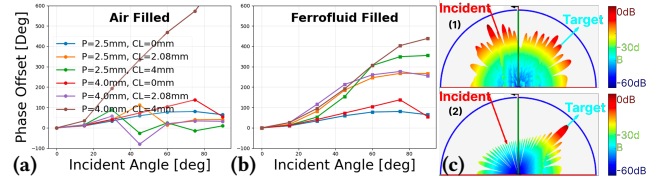


Figure 6: Beam pattern shows scattering behavior without incident angle correction.

where $\Psi_i(x, y)$ is the ideal phase shift at subarray i .

This formulation separates the optimization problem into two stages: a discrete optimization of phase distributions and a deterministic assignment of binary states. To obtain the optimal phase distributions, we employ a genetic algorithm (GA) that jointly optimizes Ψ^{air} and Ψ^{FF} across all subarrays. Each candidate solution is evaluated by measuring the constructive contribution of all unit cells toward the desired steering direction, as illustrated in Fig. 5. After G generations of selection, crossover, and mutation, the GA outputs the optimized phase distributions. AoSA with 4096 unit cells typically converge after $G = 200$. The runtime bitmap for any steering direction can then be computed efficiently using Eq. (4). The complete procedure is summarized in Alg. 1.

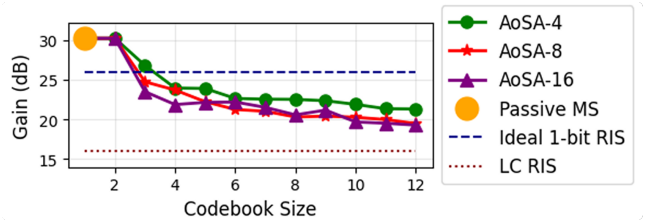


Figure 7: Average beam peak gain of FFMS-AoSA (64×64 elements) versus codebook size (number of optimized beam patterns). Smaller subarray sizes allow the AoSA gain to approach a conventional RIS.

3.2.3 Fitness Metrics. The GA-based meta-optimization framework tailors fitness function for three beam types.

For pencil beams, the objective is to maximize directivity at target angles $\Theta = \{\theta_{\text{ref},1}, \dots, \theta_{\text{ref},T}\}$ while suppressing sidelobes, where the mainlobe region is defined as $|\theta - \theta_t| \leq \Delta \theta_{\text{ML}}$. Fitness is computed from the peak-to-sidelobe ratio $\text{PSLR} = G_{\text{peak}} - G_{\text{SL}}$ aggregated across all targets as a weighted sum of average and minimum values, balancing overall gain with

worst-case suppression.

For fan beams, the goal shifts to achieving flat gain over an angular span $\Delta\theta_{\text{fan}}$, constructed by composing multiple pencil beams at discrete angles within the fan region. The fitness penalizes gain ripple (i.e., the difference between maximum and minimum gain within the fan), while rewarding average in-band gain and out-of-band suppression, prioritizing spatially uniform coverage over peak directivity.

For multi-arm beams, multiple simultaneous beams are synthesized by summing the complex steering vectors of all arm directions and extracting the resultant phase angle. The fitness rewards high per-arm gain and sidelobe suppression while penalizing inter-arm power imbalance, ensuring balanced coverage across all beam directions.

3.3 FFMS AoSA Codebook Size

Given a fixed aperture with $x \times y$ elements and $S_x \times S_y$ subarrays, each subarray contains $s_x = x/S_x$ and $s_y = y/S_y$ elements per dimension. The total number of codebook states for an AoSA configuration is $2^{s_x \times s_y}$, as each subarray switches between air-filled and ferrofluid-filled states. For an 8×8 subarray configuration, the resulting 2^{64} states are sufficient for arbitrary 2D/3D beamforming. However, when each subarray contains only 8×8 unit cells with two binary states, codebook expressiveness degrades for higher-order beam patterns. To characterize this sub-optimality, we evaluate the average beam pattern gain as a function of codebook size across different AoSA configurations sharing the same total element count. Fig. 7 demonstrates a 64×64 FFMS AoSA under varying subarray sizes and target beam counts.

Compared to conventional RIS, which restricts each element to binary phase states (0 or π) and incurs a theoretical quantization loss of ≈ 3.92 dB [5], MetaVenom maintains continuous phase control at the subarray level. Additionally, practical RIS implementations suffer significant insertion loss— ~ 4 dB for SRR-dielectric designs and ≥ 10 dB for liquid-crystal variants [48]—whereas MetaVenom's unit cell achieves below 1 dB insertion loss in both states, owing to its simple dielectric structure. Nonetheless, unlike traditional active RIS that offers element-wise phase tunability, controlling unit cells at the granularity of an 8×8 subarray restricts the spatial degrees of freedom, forcing coupled phase profiles across adjacent elements. As the target codebook size expands, the coarser spatial quantization prevents optimal phase alignment across all elements simultaneously, leading to a noticeable drop in synthesized beam peak gain (e.g., around 7.5 dB for codebook size 6).

4 Repurposing MetaVenom for Joint Radar Communication

MetaVenom's field programmability also enables a new class of joint radar-communication (JRC) metasurfaces for applications such as road work signage, billboard messaging, and electronic price boards. A field programmable tag removes the storage demand for infrequently changed static tags. The

JRC metasurface unit cells span multiple wavelengths and encode spatial variation of reflection strength across multiple mmWave FMCW radar range bins. Because the surface comprises both dark ferrofluid and colored 3D-printed thermoplastic, the same pattern is optically readable, enabling multimodal perception tags. In real world sensing conditions, robots can fall back to radar in adverse weather/lighting or to computer vision under electromagnetic interference.

We model the surface as a set of N metal-backed PLA cavities whose binary state vector $\mathbf{b} = [b_1, \dots, b_N]^\top$, $b_n \in \{0, 1\}$, encodes the tag pattern ($b_n = 0$: air-filled, $b_n = 1$: ferrofluid-filled). An FMCW radar with chirp rate $\mu = B/T_c$ illuminates the tag. After dechirping and applying a range FFT, the complex amplitude in the k -th range bin is

$$S[k] = \sum_{n \in C_k} \alpha_n \Gamma_n(f_c) e^{j \frac{4\pi f_c r_n}{c}}, \quad (5)$$

$$\alpha_n = \frac{\lambda \sqrt{G_t G_r} \sigma_n}{(4\pi)^{3/2} r_n^2}, \quad C_k = \{n : |r_n - r_k| < \frac{c}{4B}\},$$

where r_n is the range to cell n , $\sigma_n \approx w_{\text{cell}}^2$ is the geometric RCS of a cell with cross-section $w_{\text{cell}} \gg \lambda$, and C_k groups cells within the same range-bin resolution $\Delta r = c/(2B)$. Γ is the Fresnel reflection coefficient. The encoded surface pattern $\mathbf{b}$ can be recovered when the differential reflection contrast $\Delta\Gamma(f) = |\Gamma_n(f)|_{b_n=1} - |\Gamma_n(f)|_{b_n=0}|$ exceeds the radar noise floor, i.e. $\Delta\Gamma(f_c) > \alpha_n^{-1} \gamma^{-1/2}$, where γ is the per-bin SNR.

Since the front PLA-fill interface and the metal-backed return appear in separate range bins (Fabry-Perot multiple reflection [53]), the fill material determines how energy is distributed between them: ferrofluid ($\epsilon_{\text{FF}} \approx 3$) is closely matched to PLA ($\epsilon_{\text{PLA}} \approx 2.57$), allowing most of the incident energy to propagate through the cavity and reflect from the metal backing, resulting in a small front-surface reflection coefficient ($|\Gamma| \approx 0.04$). In contrast, air-filled cavities create a stronger impedance mismatch, diverting more energy toward the front-wall reflection ($|\Gamma| \approx 0.23$), producing a large differential reflection contrast $\Delta\Gamma$ at the metal range bin. By staggering cell depths, the range profile encodes $\mathbf{b}$ as a one-dimensional amplitude barcode. The resulting amplitude pattern over multiple range bins can be used to perform classification. Using small neural network or shallow tree algorithms, MetaVenom JRC tag can be classified to retrieve the encoded message.

5 FFMS Morpher Design

5.1 Ferrofluid Control

The FFMS Morpher is a programmable electromagnet array capable of generating sufficient magnetic force to lift and transport ferrofluid across the unit cell cavities. As illustrated in Fig. 8, the FFMS Morpher array is controlled using an Arduino Mega 2560 [3]. Each array element consists of a coil, a power switch, and supporting circuits. The coil has an electrical inductance of 3.7 mH [1], with an inner solenoid diameter of 8 mm, an outer diameter of 19 mm, and a height of 12 mm. In the OFF state, it is disconnected from the 12 V

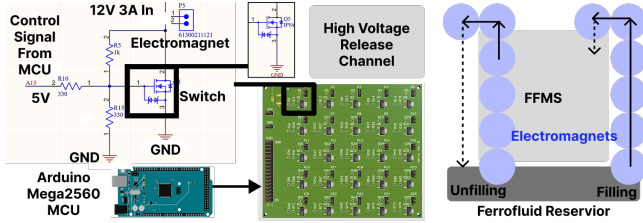


Figure 8: FFMS Morpher's circuitry consists of an Arduino and a PCB driving an array of electromagnets, where a 5 V control signal toggles each switch.

power supply, thus deactivating the magnetic field. When switched ON, the coil draws approximately 3 A of current, generating a magnetic field strong enough to attract and suspend ferrofluid. This operating point corresponds to 36 W per energized electromagnet. Power is drawn only during an activation step. The coil is disconnected between steps, and the programmed FFMS itself draws no standby power.

A practical challenge arises from inductive kickback during ON-to-OFF transitions [10], where the collapsing magnetic field induces a voltage spike that may damage switching components. To mitigate this effect, we incorporate a controlled discharge mechanism in the circuit. Specifically, feedback resistors (R5 and R15 in Fig. 8) temporarily keep the switching transistor in a conductive state when a voltage spike occurs. This allows the coil current to decay gradually rather than abruptly, significantly reducing the magnitude of the voltage spike and protecting the circuit.

The FFMS Morpher module is constructed using low-cost components, including electromagnets (\$2 each), printed circuit boards (\$1), a microcontroller unit (MCU) (\$50), and a 3D-printed housing (\$2). To accompany the 32×32 FFMS, 10 electromagnets will suffice, which leads to the total hardware cost of the FFMS Morpher module being under \$100 per unit. These figures separate the deployed surface from the reusable programmer. A 3D printed 32×32 surface material costs less than \$5, whereas the ten-coil FFMS Morpher costs approximately \$100 (25 $\times$ \$2 coils, a \$1 PCB, a \$40 MCU, and a \$2 housing). Ferrofluid, conductive coating, and any protective enclosure are additional per-surface costs; labor, printer use, assembly equipment, and test instrumentation are excluded. Because the FFMS Morpher is detachable and reusable, its cost is amortized across surfaces. Comparisons with prior work are organized in Table 2.

5.2 Reconfiguration Latency and Deployment Scenarios

Reconfiguration latency depends on the time required to transport ferrofluid between electromagnets. Experimental measurements show that moving ferrofluid from one electromagnet center to the next requires approximately $t \approx 100$ ms.

Considering an FFMS metasurface with n unit cells along one dimension, resulting in a total length of $L = n\lambda/2$. For electromagnets with a diameter of m , the minimum number of electromagnets required to support full ferrofluid trans-

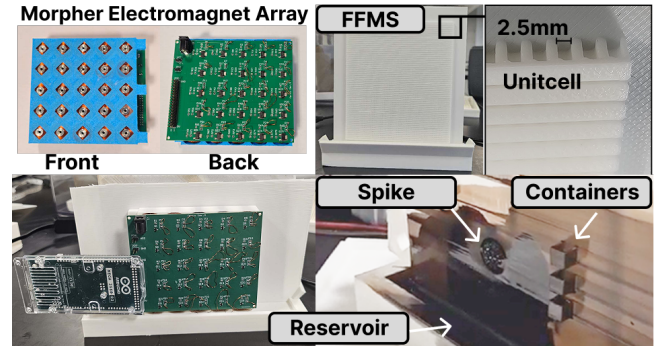


Figure 9: FFMS and FFMS Morpher prototypes.

port is approximately $M = (n\lambda/2/m + 2)$, which scales linearly with metasurface size. The total number of operations depends on the ferrofluid volume in the cavities. As shown in Fig. 8, the FFMS Morpher module only moves ferrofluid to the top or edge of the metasurface, where gravity distributes it into cavities or returns it to the reservoir.

Table 1 summarizes the power input of a single electromagnet and the corresponding ferrofluid volume that can be transported. As an example, consider an FFMS with 32×32 elements at 60 GHz. Each unit cell contains a maximum cavity volume of $2.5 \times 2.5 \times 6.2$ mm. Using an electromagnet with a diameter of 20 mm, filling the entire surface requires approximately 189 electromagnet activation operations, corresponding to a total reconfiguration time of roughly 20 s. This is a full-fill upper bound: bitmaps altering fewer sub-arrays need fewer activation and transport steps. Coil-on energy also follows the activation schedule at 36 W per energized coil, so it is reported per schedule rather than as a single aggregate. In practice, this estimate represents an upper bound because not all unit cells use the maximum cavity depth of 6.2 mm.

MetaVenom targets quasi-static environments rather than real-time beam tracking such as coverage staged before scheduled gatherings, temporary links with fixed endpoints, policies switched between work shifts, and mmWave coverage from stationary reflectors such as building walls. In these scenarios, the passive operation of MetaVenom (with a per-surface cost of approximately \$5 compared with thousands of dollars for active metasurfaces) enables cost-effective large-scale deployment. Reconfiguration can be performed during low-activity periods (e.g., overnight or between shifts) without requiring continuous power or wireless control.

6 Implementation

6.1 FFMS Fabrication

To demonstrate the feasibility of FFMS, we fabricate a single 32×32 unit cell metasurface designed for mmWave beam steering compared with baseline metasurfaces. The metasurface is 3D printed using a Bambu X1C printer, which provides $80 \mu\text{m}$ of vertical (Z-axis) precision and $400 \mu\text{m}$ of lateral (X- and Y-axis) precision when using a 0.4 mm diameter nozzle [23]. For AoSA metasurfaces, we print 2D array of

8×8 subarrays with each subarray containing 8×8 unitcells, resulting in a total of $64 \times 64 = 4096$ unitcells in an AoSA.

Printing a 32×32 metasurface requires ≈ 3.5 h and about 35 grams of PLA material [22]. Filling the 32×32 surface with ferrofluid requires ≈ 15 mL of fluid, which costs under \$10 USD [31]. Each AoSA costs less than \$5 using the same PLA material. Compared to an active RIS of \$10K USD [7] and passive PCB mmWave metasurface of \$5K USD [34], FFMS offers field programmability at passive 3D printable mmWave metasurface cost. To accurately model the metasurface's electromagnetic behavior, we measure the dielectric properties of PLA at 60 GHz using a free-space frequency-shift method, where transmission attenuation through the sample placed between two lens horn antennas connected to a VNA is swept across frequency to extract permittivity and loss tangent. The measured constants and loss tangent are 2.57 and 0.015, respectively. As shown in Fig. 9, the metasurface structure is made with PLA, and conductive paint is sprayed onto the back as a common reflective ground plane.

To validate our passive FFMS design, we compare it against three state-of-the-art passive metasurface systems operating at 60 GHz: MilliMirror [44], MetaSight [55], and AutoMS [30]. MilliMirror and MetaSight both employ PLA-based 3D-printed unitcells (the former also using conductive paint similar to our design), while AutoMS uses hot-stamped copper on paper substrate for ultra-low-cost fabrication. The beam steering performance of MetaVenom's metasurface is directly comparable to these designs.

6.2 FFMS Morpher Implementation

To support the reconfiguration of the 32×32 FFMS, we implement the FFMS Morpher module consisting of a 5×5 electromagnet array that controls the ferrofluid transport. As shown in Fig. 9, the FFMS Morpher can effectively move ferrofluid from the bottom tank reservoir into arbitrary 2D grid positions on the metasurface. Due to ferrofluid containers in all unit cells being interconnected within a single metasurface, ferrofluid can enter or exit the metasurface anywhere along the metasurface top opening. Thus, the FFMS Morpher only needs coarse, cm-level alignment with the metasurface to transport ferrofluid, and count repetitions for total amount of ferrofluid being transferred. For automatic alignment, wireless charging station's magnetic alignment on metasurface and FFMS Morpher corners can be implemented for robotics. For our evaluations, we use manual alignment that roughly

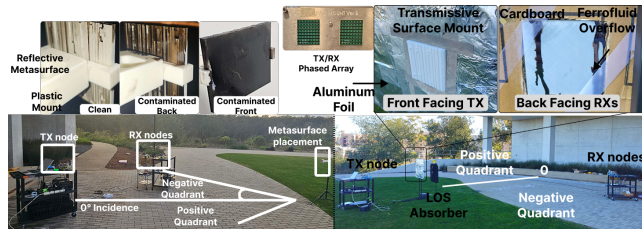


Figure 10: FFMS evaluation setup in reflective (left) and transmissive (right) settings.

places the FFMS Morpher behind the metasurface in direct contact, and moving FFMS Morpher 5mm away from FFMS will lead to no ferrofluid being transported.

Each electromagnet is 19 mm in diameter and 12 mm in thickness. The coils are insulated while wrapped around an 8 mm diameter paramagnetic metal [1]. Due to the relatively large number of coils and high voltage/current being supplied, the coil can quickly heat up to 100 °C after 20 s of continuous operation. Thus, we limit the maximum activation duration for a single electromagnet to be 1 s. After activation, it takes about 50–200 ms for an electromagnet to reach peak current and generate the maximize force. With only two electromagnets activated at a time, and power duty cycling, overheating can be prevented.

The FFMS Morpher module consists of a 3D-printed mechanical frame for mounting the electromagnets, an Arduino microprocessor for control, and a PCB that simplifies the pin-to-electromagnet connections. The total cost for the FFMS Morpher module is less than \$100. The complete FFMS Morpher assembly weighs 675 g, with each electromagnet contributing around 20 g. Even with a portable battery, the system remains light enough for commercial drones [50], enabling the target deployment scenario (Sec. 5.2).

7 Evaluation - Comm. Beamforming

7.1 Experimental Setup

For mmWave communication use cases, we utilize an upgraded version of the M-Cube SDR [58] for 60 GHz communication, equipped with 8×8 phased arrays from COTS IEEE 802.11AY [19] devices. The Effective Isotropic Radiated Power (EIRP) from the antenna is 40 dBm, in compliance with FCC's regulation [16]. Using RFSoc FPGA [46] at 1.966 GHz sampling rate, the channel impulse response (CIR) is estimated via 802.11AD/AY Golay-sequence correlation, achieving 15 cm path resolution to differentiate the FFMS path. We use the boresight pencil beam at the transmitter pointing to the FFMS, and a semi-omnidirectional receiver beam. To measure reflection beam strength at various angles and distances, we fix the transmitter at a given incident angle and move the receiver to different angles facing the FFMS. The FFMS is fixed on a tripod with mounting structure long enough to clearly separate the FFMS from tripod in reflection range bins. The setups for both reflection and transmission measurements are shown in Fig. 10. For AoSA metasurfaces, the default sub-array size is 8×8 , since our COTS electromagnets' diameter is equivalent to 8 unit cells' length. Smaller sub-array size will demand customized electromagnet design. We report the measured signal strength for the communication metasurface. The measurements in this section use the 60 GHz M-Cube link, COTS 8×8 phased arrays, a boresight transmit beam, a semi-omnidirectional receive beam, the indicated incidence/departure angles, and the indoor/outdoor environments shown in Fig. 10. Unless a figure states otherwise, the transmitter and receiver are

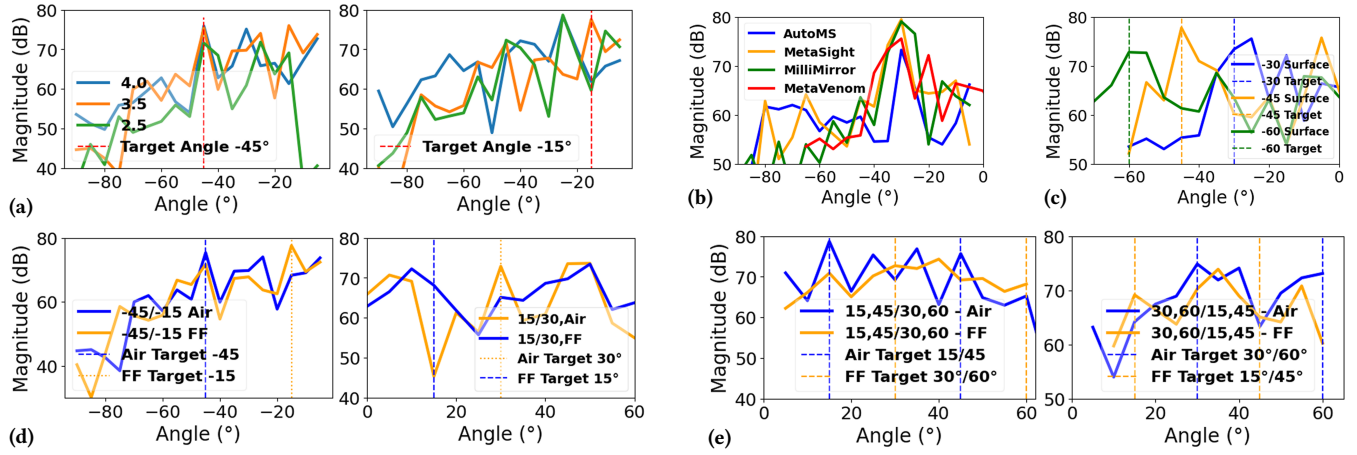


Figure 11: (a) Dielectric fitting - air-filled and ferrofluid filled results, $dK=3.5$'s ferrofluid filled pattern is closest to target (b) Baseline beam steering test compared to SoTA (c) Air filled single panel design for different angles (d) FFMS pencil beam test (e) FFMS pencil beam reconfiguration test (f) FFMS multi-armed beam reconfiguration.

each 5 m from the surface.

7.2 Dielectric Constant Correction

Recall that the oil-based ferrofluid dielectric constant was estimated as 3 (Sec. 2.1); however, each manufacturer's recipe varies in ferrite and surfactant volume ratios. We thus tested four values (2.5 to 4 with 0.5 interval) and selected the value that maximized main lobe strength to determine our ferrofluid sample's actual dielectric constant (dK).

We design all surfaces to steer to -45° without ferrofluid, and reconfigure to -15° with ferrofluid. This will clearly indicate which dK assumption will allow ferrofluid to move beam strength from -45° to -15° . As shown in Fig. 11(a), all fabricated surfaces showed the highest peak at -45° , which proves that the dielectric parameter is accurate for PLA. Fig. 11(b) shows that only the $dK = 3.5$ design achieves peak gain at the intended -15° direction, while other designs produce off-target peaks at -25° . This verifies that our ferrofluid exhibits $dK = 3.5$ at 60 GHz, close to the theoretical predictions from Maxwell-Garnett mixing theory. For all following evaluations, we will model ferrofluid with $dK = 3.5$.

7.3 Beam Steering Evaluations

7.3.1 Baseline Comparisons. We fabricate AutoMS, MilliMirror, and MetaSight surfaces as our baseline. Our surface is configured for air-filled beam steering only, and all base-

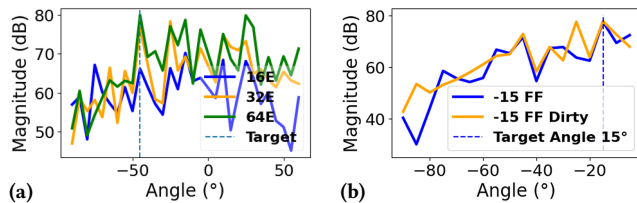


Figure 12: (a) Performance with different number of elements (b) Beam pattern w/ and w/o ferrofluid contamination on both of the reflection front and back.

line test surfaces are designed to steer from 0° to -30° in the same setting. As shown in Fig. 11(c), designed FFMS's beam steering capability is comparable to SOTA baseline surface designs. Due to additional thickness from FFMS's multi-layered unitcell, FFMS's reflection peak signal strength is slightly lower than thin PLA designs in MilliMirror and MetaSight, while still higher than AutoMS's lossy PCB SRRs.

7.3.2 Pencil Beam. We first validate our metasurface's pencil beam steering capability in its initial state without ferrofluid. As shown in Fig. 11(c), FFMS surfaces produce strong, distinguishable beams at target angles well above the noise floor. Although there are side lobes, at -15° for the surface targeting -30° , and -5° for all of the surfaces, it is inevitable due to the unitcells radiating energy to all directions. As the reflection widens to -60° , the peak magnitude decreases, which is due to wide angle suffering shadowing effect from adjacent unitcells when RF wave exits the cell, which causes additional attenuation in amplitude. The results match with our simulated result including the potential grating lobes. Although grating lobe suppression algorithms can be used for additional security and privacy features, it is beyond the scope of this work.

7.3.3 Reconfiguring Pencil Beam. To show FFMS's capability in resteeering the pencil beams with ferrofluid filled, we fabricate two representative metasurfaces of 32×32 size, with $15^\circ \leftrightarrow 30^\circ$ and $-45^\circ \leftrightarrow -15^\circ$ configurations (i.e., first number shows air-filled pencil beam, and second number shows ferrofluid filled pencil beam). As shown in Fig. 11(d), FFMS can steer the beam in both the positive and negative quadrants, with $\pm 15^\circ$ and $\pm 30^\circ$ beam angle offsets. This proves FFMS's phase model correctness in the lookup table with both air-filled and ferrofluid filled phase pattern to dielectric thickness mapping. For indoor applications, pencil beam reconfiguration will suffice simple usage.

7.3.4 Reconfiguring Multi-armed Beam. To showcase FFMS's capability in reconfiguring arbitrary beam patterns, we fabri-

cate two surfaces, each with a multi-arm beam on an air-filled pattern and a multi-arm beam on a ferrofluid filled pattern. Specifically, the configuration of the first surface is: 0° incidental and $30, 60^\circ \leftrightarrow 15, 45^\circ$ reflecting beam directions. The 0° incident, $15, 45^\circ \leftrightarrow 30, 60^\circ$ pattern is the exact opposite configuration of the first surface, which tests symmetric beam reconfiguration control. As shown in Fig. 11(e), both surfaces exhibit substantial gain at the targeted steering angles for each ferrofluid-filled configuration. Air-filled patterns generally exhibit higher magnitude, as ferrofluid-filled unit cells introduce approximately 1 dB of insertion loss, which remains acceptable for practical deployment.

7.4 AoSA Evaluation

To validate MetaVenom's beam pattern accuracy with AoSA bitmaps beyond binary beam pattern shift, we test pencil, fan, and multi-armed beam patterns; full phase distributions, bitmaps, and ideal simulated results are provided in the Appendix, with real-world measurements presented in the following subsections.

7.4.1 AoSA-Pencil Beam. We test AoSA with codebook containing five pencil beams targeting 10° to 50° , at 10° interval, each with a beam width of 3° . As shown in Fig. 14(a), the measured beam patterns align with the designed targets, and the corresponding ferrofluid infill bitmaps are provided in Appendix Fig. 21. Resulted pencil beams are sharp and at least 5-10 dB higher than the side lobes created by the metasurface. These pencil beams also verifies that it has beam strength magnitude comparable to fully passive surfaces without extra thickness of ferrofluid containing structure, as previously shown in Fig. 11(c).

7.4.2 AoSA-Fan Beam. We test an AoSA with codebook containing three fan beams targeting 15° , 30° , and 45° with a beam width of 10° . As shown in Fig. 14(b), the measured beam patterns completely cover the designed angular sectors, with average magnitude approximately 20 dB above the noise floor. The corresponding ferrofluid infill bitmaps are provided in Appendix Fig. 23. Resulted fan beam patterns completely covers the designed angular sector with average beam magnitude being ~ 20 dB higher than the 50 dB noise floor. Fan beams spread the same total radiated power across a wider angular sector than pencil beams, resulting in inherently lower power density at any point within the coverage area. In our measurements, the average fan beam magnitude is approximately 5 dB lower than the pencil beam peak at the same center angle, consistent with the simulated beam pattern in Appendix Fig. 21(c) vs. Appendix Fig. 23(c).

7.4.3 AoSA-Multi-armed Beam. Lastly, we test an AoSA with codebook containing three multi-arm beams with arbitrary two-arm designs, where each arm targets an angle within $[10^\circ, 60^\circ]$ at 5° intervals. The tested configurations are $30^\circ/40^\circ$, $20^\circ/55^\circ$, and $15^\circ/45^\circ$, corresponding to angular separations of 10° , 35° , and 30° , respectively. As shown in Fig. 14(c), the measured multi-arm beam patterns exhibit two distinct peaks at the designed angles with low sidelobe

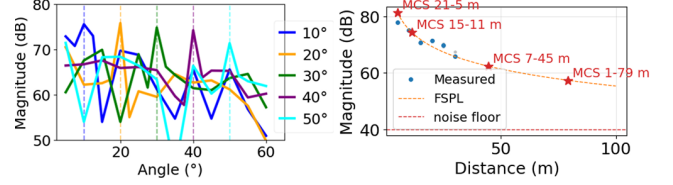


Figure 13: (left) AoSA evaluation result with codebook containing 5 pencil beams on the same MetaVenom surface. (right) Distance measurement and FSPL model.

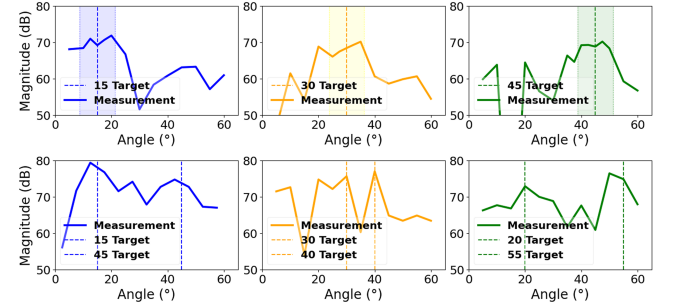


Figure 14: AoSA evaluation result for (a) three fan beams each with 10° beam width, on a second MetaVenom surface (b) three two-armed beams from the third MetaVenom surface.

levels. The peak magnitude is comparable to that of pencil beams and higher than that of fan beams. While the sidelobes added up from two pencil beam phase array stacking on top of each other, the two armed beam is clearly distinguishable with peak position matching targeted angles, also shown in Appendix Fig. 24(c).

7.5 Link Budget Analysis

Our MetaVenom FFMS's signal strength for pencil beam with codebook size of five is evaluated at various distances. Fig. 13 shows measured signal strength follows freespace path loss (FSPL) model with x being distance and y being reflected signal magnitude in dB, and $y = -20 \log_{10}(x) + 95.33$. With the MetaVenom metasurface, we can illuminate a pencil beam direction with signal 40 dB above noise floor with receiver being an omnidirectional antenna. With our FSPL model fitting, the reflected signal can go beyond 79 m while qualifying for MCS1 in IEEE 802.11ay standard [19].

7.6 Number of Elements

We test reflecting gain versus edge size E , evaluating FFMS at 16E, 32E, and 64E (4 cm, 8 cm, and 16 cm), with the transmitter and receiver each measured at 5 m from the surface. As shown in Fig. 12(a), signal strength at -45° increases sharply with edge length. Increasing from 16E to 32E provides a 10 dB gain, which is close to the theoretical gain of 12 dB with $4\times$ reflection area/power. However, the 4 dB improvement from 32E to 64E is limited by receiver saturation, in which the receiver phased array has reached its highest analog power output. For indoor applications, 32E (8 cm edge length) fits seamlessly into home and office environments,

would suffice performing coverage expansion. The extension of outdoor coverage would benefit from 64E or larger arrays for longer ranges and larger areas. However, near-field effects, where curved wavefronts reduce effective aperture and beam quality, scale with surface size as $r_{nf} = 2D^2/\lambda$. At 60 GHz, our 32E array (8 cm) has $r_{nf} = 2.6$ m, while 64E (16 cm) extends to 10.2 m. A 1 m aperture would require a 400 m far-field range. However, resolving the near-field effect is beyond the scope of this work.

7.7 Impact of Ferrofluid Residuals

Ferrofluid migration inevitably contaminates the front, back, and residual fluid within unit cells. Thus, we evaluate the performance impact of ferrofluid contamination on both front (towards the RX) and the back (behind metal paint) after completing a fill/unfill cycle of the surface, as demonstrated in Fig. 10. The thickness of residual fluid in each container is ≤ 0.1 mm. Although such deposits can shift air-filled state phase pattern, its primary beam pattern is unaffected.

The performance of our surface towards the main lobe is not impacted by either front or back contamination, and residual ferrofluid, as shown in Fig. 12(c). This shows that our reconfigurable passive surface can be used and reconfigured repeatedly without additional maintenance.

7.8 Angular Coverage of Radiation Pattern

All existing metasurfaces suffer from wide angle beam patterns (i.e., reflection/transmission angle wider than $\pm 60^\circ$). Part of the problem comes from antenna/meta-element's geometry design being completely flat, which does not radiate energy equally within $\pm 90^\circ$ field of view. To assess whether surface front geometry will improve wide angle beam steering performance, we evaluate the surfaces designed for wide angle reflection (e.g., 0° incident and $70/80^\circ$ reflection pencil beam) with an air-filled pattern. As shown in Fig. 15 (a), surfaces fabricated with flat, hemispherical, and triangular fronts produce different patterns at the edge of its reflection spectrum. Unlike the rapidly attenuating cuboid model, the wedge modeled surface validates the simulation (Fig. 4) with periodic gains at discrete angles. The spherical model also achieves higher gain at both target angles, outperforming the wedge at -70° while losing to wedge model at -80° . In summary, the wedge model demonstrates that angled unit-cell facets can yield gain at ultra-wide angles.

7.9 Transmissive Pencil Beam Reconfiguration

The transmissive FFMS is positioned 5 m from both the transmitter and receiver, with the transmitter aligned at the surface boresight. To ensure that signals propagate exclusively through the transmissive surface, aluminum foil is applied to the surface mount and a line-of-sight (LoS) absorber is employed to block direct paths. Fig. 15(b) demonstrates that the transmissive surface successfully generates the desired pencil beam pattern before and after reconfiguration, supporting

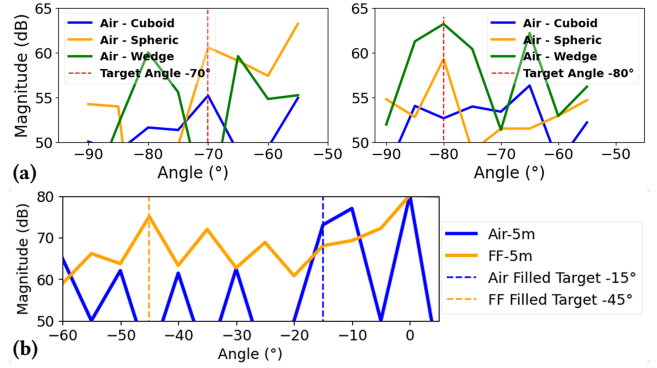


Figure 15: (a) Different unitcell front design shows varied performance across for extremely wide angles. (b) Transmissive surface results with air-filled and ferrofluid filled targets being -15° and -45° , respectively.

arbitrary beam patterns in both air-filled and ferrofluid-filled configurations. Similar to the reflective surface's specular reflection, the pass through signal strength at 0° is comparable to the main lobe peaks. This can be mitigated through surface and null steering design that further suppresses the undesired lobes in optimization metric and cost function. In summary, this proves that FFMS works in both reflection and transmission mode, thus accommodating different TX/RX deployment settings.

8 Evaluation - Real World Case Study

To demonstrate MetaVenom's capability in real world settings, we select an underground tunnel connected to a wide space, in which any straight line drawn for mmWave pencil beam will result in inadequate coverage. As shown in Fig. 16, the real world setup places the AP (TX) in the middle of the tunnel 11 m from the FFMS, and the RX to sweep end of the open space. We use a $-50^\circ \leftrightarrow 30^\circ$ reconfigurable metasurface to examine FFMS's capability to steer the beam from the negative to the positive quadrant. Fig. 16 (right) shows the ferrofluid-filled beam pattern concentrating energy to the right, whereas the air-filled pattern steers to the left. Before reconfiguration, position 3 shows slightly elevated signal strength above baseline due to FFMS reflection. After reconfiguration, positions 15 and 16 have significantly higher signal strength, showing evident contrast to the left side. Overall, these experiments demonstrate MetaVenom's effectiveness in reconfiguring different beam patterns.

9 Evaluation of the JRC Use Case

Roadside infrastructure (e.g., traffic signs, price displays) can embed JRC-enabled metasurfaces, enabling passive radar detectability that persists across FFMS Morpher reconfigurations without LED power or paper fragility.

9.1 Experimental Setup for JRC

To experiment with the JRC tag, we utilize TI AWR1843BOOST [51] radar that operates from 77 to 81 GHz with a range resolution of 3.75 cm, and chirp slope of 30 MHz/ μ s. The EIRP

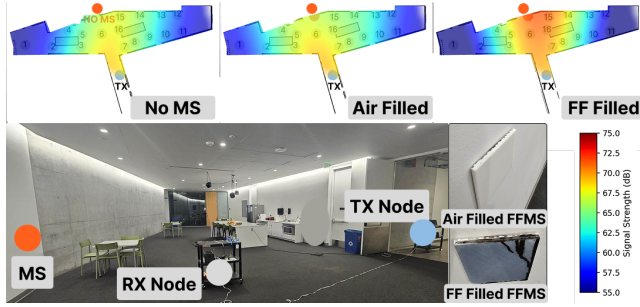


Figure 16: Real world reflective FFMS case study. As FFMS filling changes, beam pattern shifts from left side of the space to the right side, with significant signal strength pattern shift shown in the heatmaps.

from the radar antenna is 22.5 dBm (≈ 180 mW) per active TX channel, and only one TX antenna is active during our measurement [51]. Given the width of FFMS tag and dielectric thickness in the JRC deployment, its presence will occupy $\approx 3-6$ range bins. Tags are placed 5 m to 30 m away from the radar. While the distance is limited to 30 m in our setup, the radar can detect the tag up to the limit of its detection range. Unit cell patterns follow AprilTag [37], whose two-color design maps to filled/empty packets, enabling n -bit coding where n is the number of packets. Visual tags use black-and-white checkerboard patterns; our MetaVenom JRC tag uses filled/empty unit cells instead. The filling pattern modulates signals into distinct range profiles that are decodable.

We fabricate a single JRC tag and program it to display 8 tags [37] in the 36h11 family, with ID# ranging from #1 to #8. Each tag has a 6×6 array of 2×2 cm ferrofluid packets that are reconfigurable, which means 36 bit coding capacity. As shown in Fig. 17, the radar is facing the AprilTag and the metasurface, where an array of unit cell containers sign different patterns. The resulting ADC data from the radar is fed to a shallow 2-layer perceptron for tag id classification. Example tag patterns are shown in the Fig. 20. At each position, we collect 1024 data points for each tag pattern. Data collected are split into training and testing set in 1:1 ratio to prevent contamination.

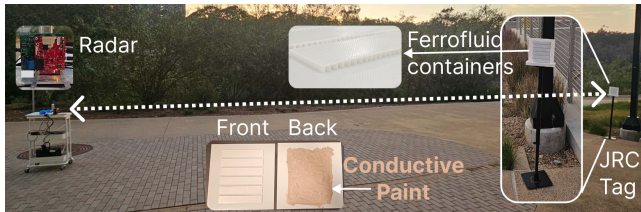


Figure 17: FFMS 6×6 grid for JRC setup. Radar is directly facing the tag to characterize the tag’s ferrofluid infill patterns at long range.

9.2 General Evaluation for JRC Tag

We evaluate JRC tag classification performance at 5 m with 8 tag patterns. As shown in Fig. 18, the confusion matrix shows an average of above 90% accuracy on all tag patterns, and different tags with different ferrofluid infill geometries can be

clearly distinguished. FFMS’s 8 AprilTag patterns enable 3-bit encoding, with larger size tag opening up larger encoding space. In addition, feature-space expansion (antennas, ADC samples, chirps) resolves similar patterns, validating FFMS as a field-programmable JRC tag.

9.3 Distance Impact

When the tag is placed at different distances from the radar, the radar’s perceived signal to noise ratio varies. To validate our JRC tag’s resilience against distance change, we move the radar from 5 m up to 30 m at 5 m distance interval, and the tag remains untouched. As shown in Fig. 18, the classification performance is maintained above 90%, which echoes the tag’s high reflection SNR of ≥ 20 dB. This is benefiting from the conductive paint backing the 3D printed structure that FerroTag [25] lacks, which limited their sensing range to around 1 m. Overall, as long as the tag’s SNR is sufficient at the receiver side of the radar, the tag recognition accuracy will remain high.

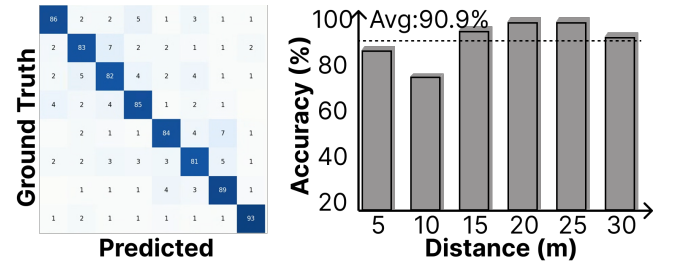


Figure 18: (Left) Confusion Matrix for tag classification. (Right) Classification accuracy over distance up to 30 m.

10 Related Work

Reconfigurable Intelligent Surfaces (RIS): RIS have garnered significant interest due to their ability to manipulate electromagnetic wavefronts. Previous work has demonstrated a variety of RIS architectures, including low-cost reflection arrays for beam steering [4, 6, 26, 56], transmissive surfaces that enable new deployment scenarios such as indoor coverage expansion [7], unit cell grouping techniques that extend communication range [17], and multi-metasurface coordinated communication [24]. Additional efforts have addressed power-efficient designs [20] and flexible PCB implementations for in-body communication [28].

Most RIS use active per-unit-cell phase tuners (PIN diodes, varactors), costing approximately \$10K at mmWave [7] before power and control infrastructure (Table 2). Neuder et al. [32] substitute liquid crystal for varactors at 60 GHz, but suffer poor efficiency and still need costly low-loss PCB fabrication. MetaVenom’s FFMS contains no electronic components. Fixed passive surfaces reconfigure only by replacement, mechanically reconfigurable ones carry persistent actuators, and active RIS [17, 45] offer microsecond per-element control but demand embedded hardware and powered deployment. MetaVenom instead reconfigures at AoSA granularity in ≈ 20 s via a detachable, reusable controller,

then operates fully passively.

Fully Passive Metasurface: As an alternative to active RIS, passive metasurfaces trade off reconfigurability for low-cost fabrication. These designs rely on fixed geometric structures acting as an fixed phased shifting array. For example, MilliMirror [44] demonstrated a low-cost passive metasurface fabricated by conductive ink on 3D-printed plastic structures. Similarly, Metasight [55] explored PLA-based metasurface structures optimized for sensing applications. AutoMS [30] further reduced fabrication cost by hot-stamping copper pattern onto paper-PVC substrates and combining multiple passive surfaces to extend coverage. FlowForm [59] orchestrates such passive metasurfaces into a network to further enhance coverage. Other work has explored passive metasurface designs for satellite communication using Huygens metasurface structures [39], as well as diffraction-based metasurface using low-cost engineering materials [38]. Passive metasurfaces have also been explored for JRC [33, 60]. However, existing approaches either lack reconfigurability or exhibit practical limitations: scrolling actuators [29] require per-unit-cell actuation, manual “magic cube” tuning [9] limits mmWave scalability, and panel-swapping [34] introduces storage and deployment overhead. In contrast, MetaVenom combines ferrofluid-based unit cells with a detachable magnetic reconfiguration module, preserving the low cost and zero standby power of passive designs while enabling field programmability comparable to active RIS systems.

Ferrofluid as RF material: Ferrofluid has a field-dependent electromagnetic response [18, 52], and has been used for absorbers [54], mmWave tag [25], terahertz modulators [27], and reconfigurable optics [57]. Such applications all read the fluid as a bulk amplitude medium. Unlike FerroTag’s dried-ink paper tags whose amplitude fingerprint is set at print time [25], MetaVenom unprecedentedly models liquid ferrofluid via phase-tunable unit cells. This makes MetaVenom viable for both communication and sensing applications at long range, with both beams and tag identities field-rewritable via the FFMS Morpher. Overall, MetaVenom is the first to treat ferrofluid as a spatially addressable *phase* element. It creates magnetically rewritable liquid cells whose phase shift follows from mixture permittivity and cell geometry, enabling mmWave beam synthesis and rewritable JRC tags.

11 Discussion

FFMS Lifetime Analysis. Ferrofluid safety is chemistry dependent. While most ferrofluids used in industrial sealing applications can irritate human skin, MetaVenom can instead use a biocompatible ferrofluid built from the same base materials, ferrite nanoparticles suspended in a hydrocarbon carrier [49]. In our open-surface observation, a completely filled 32×32 E surface became approximately half filled after 30 days and dried after approximately 60 days. To prevent ferrofluid from evaporating, a hermetic seal can be 3D printed to prevent ferrofluid liquid drying, weatherproof sealing is standard for deployed RF devices. The overall cost for a

sealed 32×32 E metasurface remains under \$5 USD with its only material comprising ferrofluid and 3D printed PLA. At disposal, its PLA is recyclable and environmentally friendly [40] and ferrofluid in small volume can be reused for other industrial purposes [13].

Position against existing surfaces. FFMS presents an alternative in metasurface design principle using electromagnet-actuated ferrofluid. The current system is slower than electronically controlled RIS and is not intended for fast channel tracking. It occupies a middle point between fixed passive surfaces that require storing every metasurface pattern, and physical replacement to change a beam; mechanically reconfigurable passive surfaces, which retain actuators at the deployment; and active RIS, which provides fast, fine-grained control but embeds powered electronics. MetaVenom’s main drawback is the reprogramming duration and AoSA-level granularity. This tradeoff is appropriate only when reconfigurations remain useful for operating periods much longer than the programming interval.

Frequency scope. MetaVenom is validated at 60 GHz, and is suitable to other mmWave or higher frequencies. For lower frequency such as sub-6 GHz, the limitation comes from unit cell scaling with $\lambda/2$ (2.5 mm at 60 GHz) in 3 dimensions. For sub-6 GHz frequencies, per-cell volume grows $10^3 = 1000$ times that makes the ferrofluid volume impractical to deploy.

Range and other limitations. MetaVenom has no intrinsic operating range: as a passive surface, its communication reach follows the two-hop transmitter–surface–receiver link budget and its JRC-tag reach the two-way radar equation, so both are set by the host system’s power, gains, and detection criteria rather than by the surface itself. The prototype’s real limits are its fill latency, coil heating, and FFMS Morpher to AoSA contact distance.

12 Conclusion

In this work, we designed, validated, fabricated, and field tested MetaVenom, a novel quasi-dynamic RF metasurface via ferrofluid morphing. Our design sheds light on adding reconfigurability to passive metasurfaces, extending their low-cost advantage with reconfigurability. We designed a 3D printable metasurface that can interact with ferrofluid to alter its beam pattern. We presented FFMS’s deployment in tagging for joint radar communication applications, radiation pattern and beam pattern manipulation for RF communication applications. We position MetaVenom as a quasi-static alternative between electronically controlled RIS and fixed passive metasurfaces. The demonstrated 60 GHz prototype trades fast channel tracking for detachable field reprogrammability and zero standby surface power.

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A Single Metasurface Phase Array Design and Beam Pattern Simulation Process

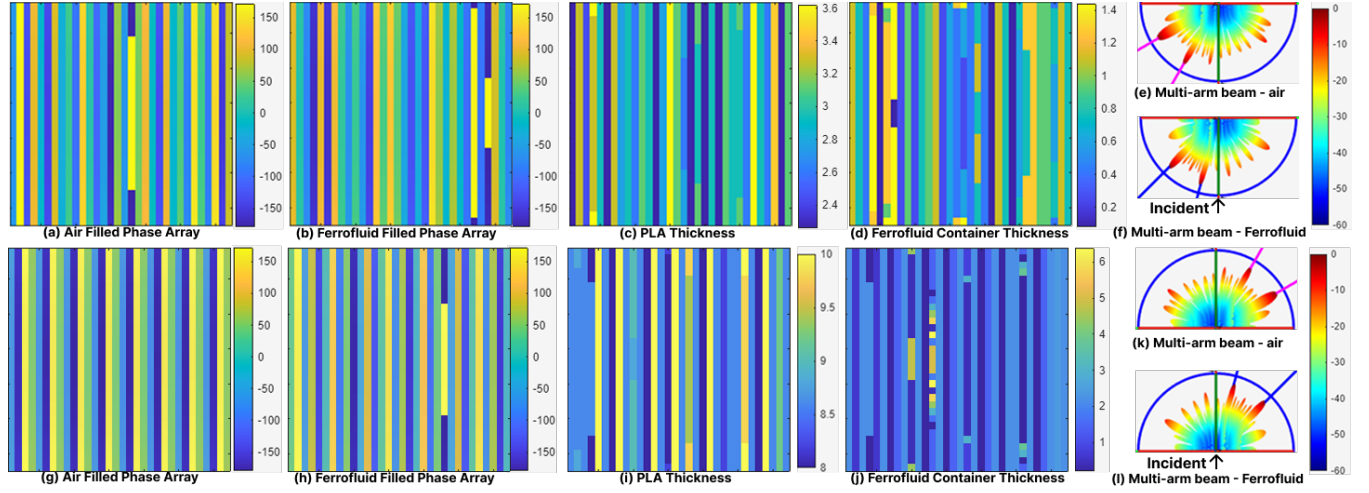


Figure 19: Ferrofluid reconfiguration for reflective (a-f) and transmissive (g-l) FFMS. For reflective FFMS, 2 configuration of phased array is shown in (a) and (b), phased array inputs generate PLA thickness (c) and ferrofluid container length (d), both (c) and (d) are used to fabricate the reflective FFMS, while (a) and (b) generates simulated beam pattern (e) and (f), respectively. Similarly, 2 configuration of transmissive FFMS phased array is shown in (g) and (h), which leads to PLA thickness (i) and ferrofluid container length (j). Both (i) and (j) are used to fabricate the transmissive FFMS, while (g) and (h) generates simulated beam pattern (k) and (l), respectively. With the same incident wave vector k_{inc} for both reflective and transmissive surfaces, the transmissive surface requires greater thickness ($\approx 2\times$) than the reflective surface because the incoming wave experiences a round-trip phase delay (in and out) in the reflective model, while experiencing only a single-pass phase delay in the transmissive model.

B FFMS Morpher Power Efficiency Analysis

Table 1: FFMS Morpher C: Current, P: Power, D: Ferrofluid spike diameter, H: Spike height, V: Ferrofluid volume being attracted by a single electromagnet.

C (A)	P (W)	D (mm)	H (mm)	V (mm ³)
1.0	12	3	2	9.4
1.5	18	10	3	157
2.0	24	20	5	1047
2.5	30	20	7	1466
3.0	36	20	7	1466

C AoSA Optimization Algorithm

Algorithm 1 AoSA Genetic Algorithm Optimization

Require: Target angles $\Theta = \{\theta_1, \dots, \theta_T\}$, subarray grid $S \times S$, population size P , generations G , beam type $\mathcal{B} \in \{\text{pencil, fan, multi-arm}\}$

Ensure: Optimized phase patterns $\Phi^{\text{air}*}, \Phi^{\text{FF}*}$; bitmap function $\mathcal{M}(\theta)$

```

1: Initialize population  $\{\Phi_p^{\text{air}}, \Phi_p^{\text{FF}}\}_{p=1}^P$  with random continuous phases  $\in [0, 2\pi)$ 
2: for  $g = 1$  to  $G$  do
3:   for each individual  $p = 1$  to  $P$  do
4:     for each target angle  $\theta_t \in \Theta$  do
5:       // Analytical bitmap selection
6:       for each subarray  $(i, j)$ ,  $1 \leq i, j \leq S$  do
7:         Compute ideal steering phase  $\Psi_{i,j}(\theta_t)$  via Eq. (1)
8:         Compute center-phase error:  $e_{i,j}^{\text{air}} = |\Phi_{p,(i,j)}^{\text{air}} - \Psi_{i,j}(\theta_t)|$ 
9:         Compute center-phase error:  $e_{i,j}^{\text{FF}} = |\Phi_{p,(i,j)}^{\text{FF}} - \Psi_{i,j}(\theta_t)|$ 
10:        Assign bitmap:  $\mathcal{M}_{i,j}(\theta_t) = \begin{cases} 0 \text{ (air)}, & e_{i,j}^{\text{air}} \leq e_{i,j}^{\text{FF}} \\ 1 \text{ (FF)}, & \text{otherwise} \end{cases}$ 
11:      end for
12:      Compose full array phase from  $\Phi_p^{\text{air}}, \Phi_p^{\text{FF}}$  using bitmap  $\mathcal{M}(\theta_t)$ 
13:      Compute array factor and beam pattern  $\mathbf{AF}(\theta; \theta_t)$ 
14:    end for
15:    Evaluate fitness  $f_p \leftarrow \mathcal{F}_{\mathcal{B}}(\mathbf{AF})$  based on beam type  $\mathcal{B}$ 
16:  end for
17:  Rank population by fitness; select top individuals
18:  Apply crossover and mutation on  $\{\Phi_p^{\text{air}}, \Phi_p^{\text{FF}}\}$ 
19: end for
return  $\Phi^{\text{air}*}, \Phi^{\text{FF}*} \leftarrow$  best individual;  $\mathcal{M}(\theta) \leftarrow$  on-demand bitmap via center-phase matching

```

D Active and Passive Metasurface Comparisons

Table 2: Comparison with active RIS, fixed passive metasurfaces, and mechanically reconfigurable passive surfaces. Freq.: operating frequency in GHz; ReCFG: reconfiguration granularity; Cost: reported surface or prototype price in USD (values are not necessarily like-for-like because cited systems include different components); C/E: reported cost per element; Pwr: standby power, or standby | reconfiguration power where both are available. The MetaVenom cost is for PLA and ferrofluid only and excludes conductive coating, enclosure, labor, equipment, and the reusable FFMS Morpher. For MetaVenom, cost is calculated from a 32x32 metasurface, 36 W is consumed per energized electromagnet only during reconfiguration, and the programmed surface consumes no standby power. EM: electromagnet; SM: servo motor.

System	Freq	ReCFG	Cost	C/E (\$)	Pwr
LAIA [26]	2.4	✓	≈ 100	1.75	14 mW
ScatterMIMO [12]	5	✓	450	≈ 1	≈ 1 W
RFLens [17]	5	✓	246	< 1	mWs
Diffract [38]	5	×	33	≤ 0.25	0
Scrolls [29]	0.9–6	Row	156	≈ 3	0 4.2W/SM
mmWall [7]	24	Col	≈ 10 K	≈ 5	≈ 100 μW
NR [20]	24	Col	600	≈ 1	0 μWs/SM
PMSat[39]	20	×	30	≤ 1	0
MilliMirror[44]	60	×	15	≪ 0.01	0
AutoMS[30]	60	×	≈ 2	≪ 0.01	0
MetaVenom (Ours)	60	AoSA	< 5	≪ 0.01	0 36W/EM

E JRC Tag Spectrum Examples

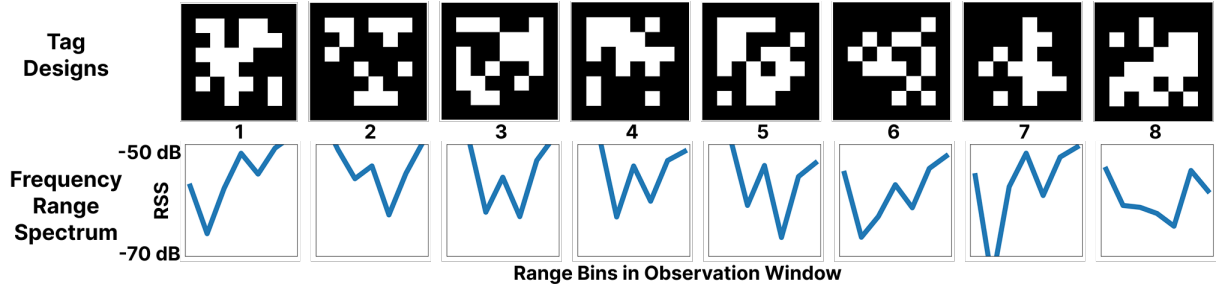


Figure 20: Example frequency range spectrum of MetaVenom JRC tags with different range bin reflection signal strength (RSS) dependent on air-filling or ferrofluid-filling of its 6x6 grid.

F AoSA Optimization Simulation Results

F.1 AoSA for Pencil Beams – 10 Degree Interval

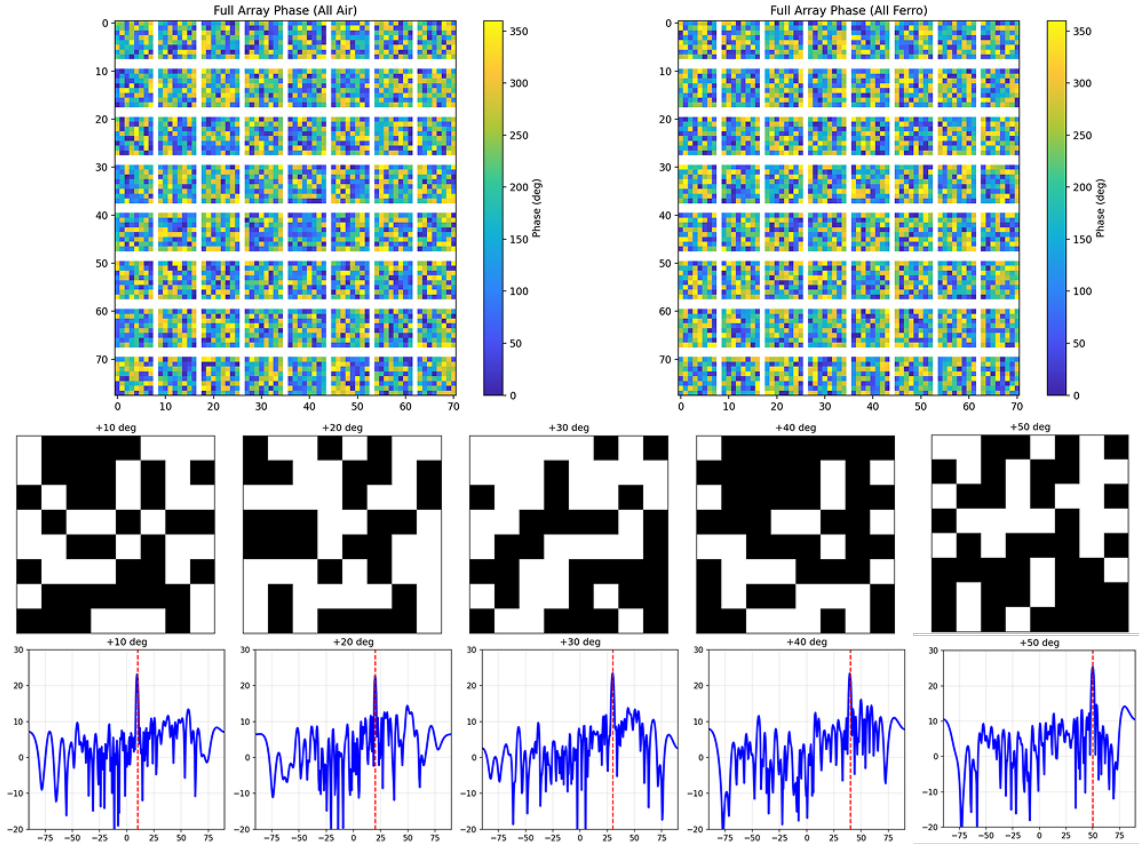


Figure 21: (a) AoSA phased array for pencil beam patterns, air-filled pattern (left) and ferrofluid-filled pattern (right). Each subarray has 8×8 unitcells, with 8 subarrays in horizontal axis and 8 subarray in vertical axis, totaling to 4096 unitcells. (b) Optimized bitmap for 10° , 20° , 30° , 40° , and 50° pencil beams with 3° half power beam width. The resulting beam signal strength is ~ 23 dB for all five pencil beam angles. This grants FFMS the capability to steer like an active RIS, but with memristive states.

F.2 AoSA for Pencil Beams – 12 Beams

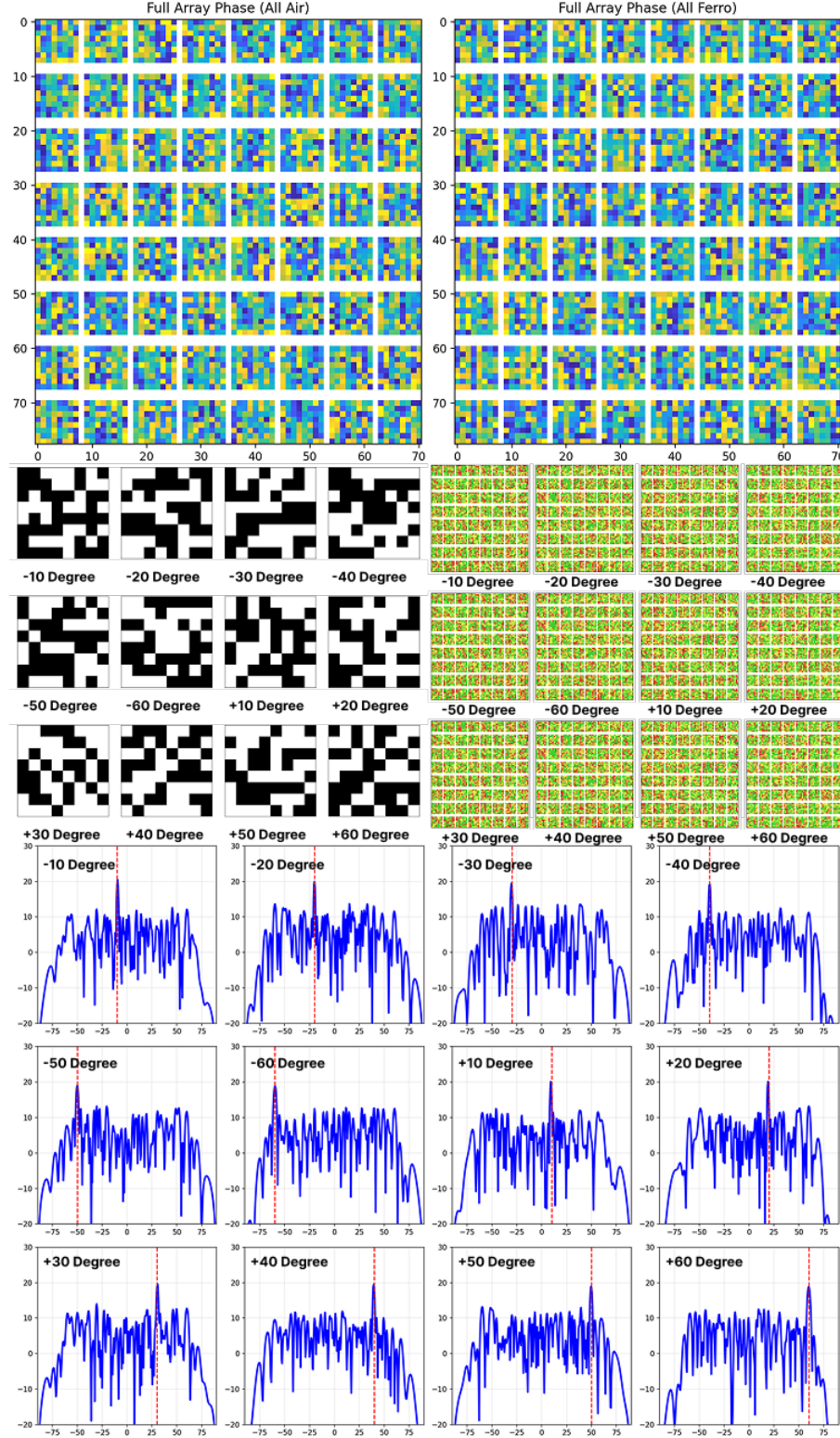


Figure 22: Top to bottom: (a) AoSA phased array for pencil beam patterns, air-filled pattern (left) and ferrofluid-filled pattern (right). Each subarray has 8×8 unitcells, with 8 subarrays in horizontal axis and 8 subarrays in vertical axis, totaling to 4096 unitcells. (b) Optimized bitmap and cell contributions.

F.3 AoSA for Fan Beams

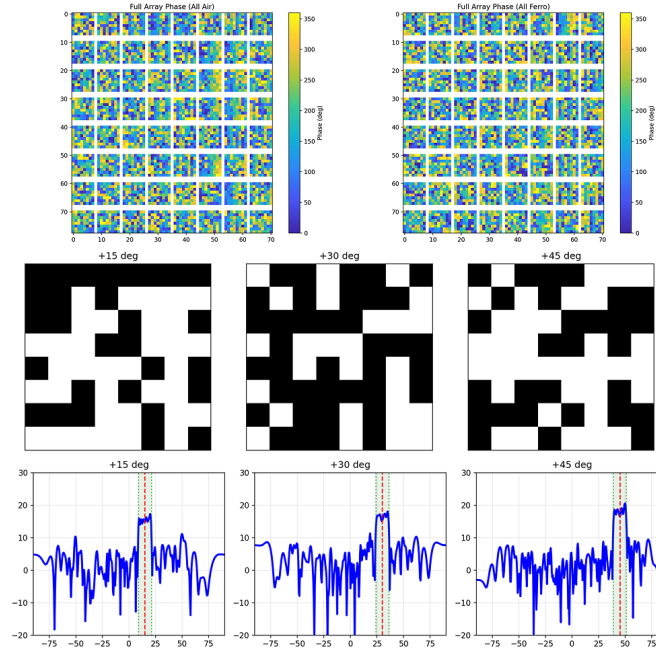


Figure 23: From top to bottom: (a) AoSA phased array for fan beam patterns, air-filled pattern (left) and ferrofluid-filled pattern (right). Each subarray has 8×8 unitcells, with 8 subarrays in horizontal axis and 8 subarrays in vertical axis, totaling to 4096 unitcells. (b) Optimized bitmap for 15°, 30°, 45° fan beams with 12.5° fan width. The resulting beam signal strength is ~ 18 dB.

F.4 AoSA for Multi-armed Beams

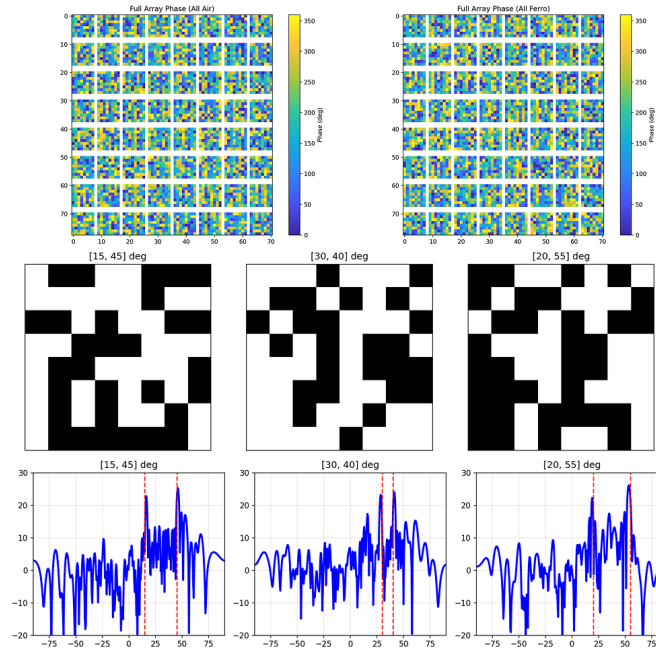


Figure 24: From top to bottom: (a) AoSA phased array for two-armed beam patterns, air-filled pattern (left) and ferrofluid-filled pattern (right). Each subarray has 8×8 unitcells, with 8 subarrays in horizontal axis and 8 subarrays in vertical axis, totaling to 4096 unitcells. (b) Optimized bitmap for 15°, 30°, 45° fan beams with 12.5° fan width. The resulting beam signal strength is ~ 23 dB.

F.5 Ultra Large AoSA

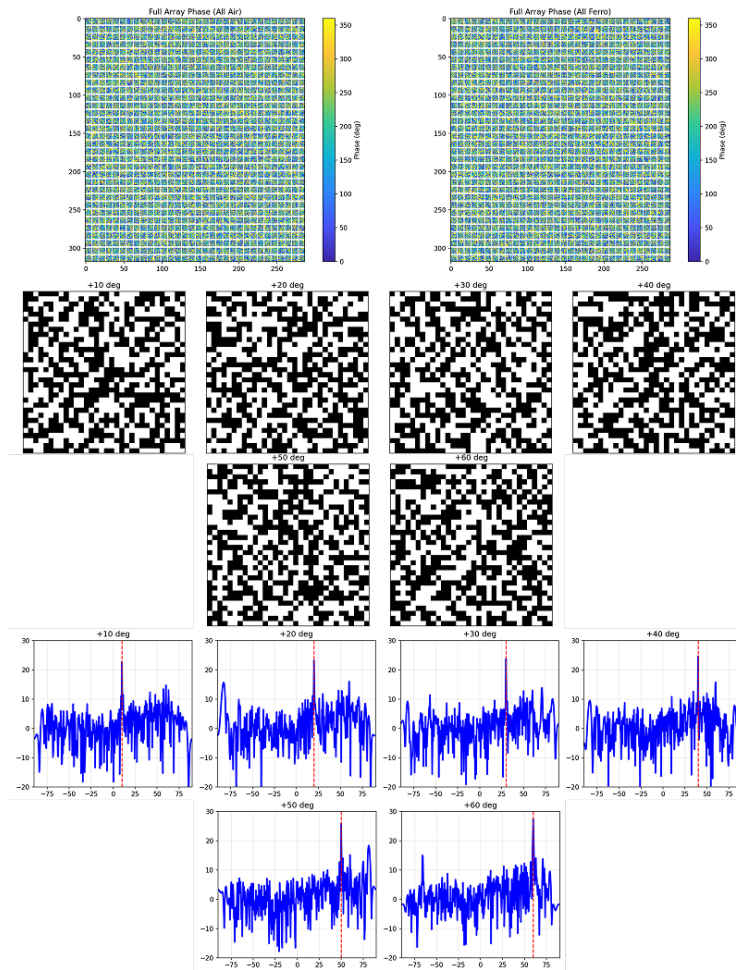


Figure 25: (a) Ultra large AoSA phased array for pencil beam patterns, air-filled pattern (left) and ferrofluid-filled pattern (right). Each subarray has 8×8 unitcells, with 32 subarrays in horizontal axis and 32 subarrays in vertical axis, totaling to 65,536 unitcells. (b) The resulting beam signal strength is ~ 25 dB for all six pencil beam angles. This grants FFMS the capability to steer like an active RIS, but with memristive states.

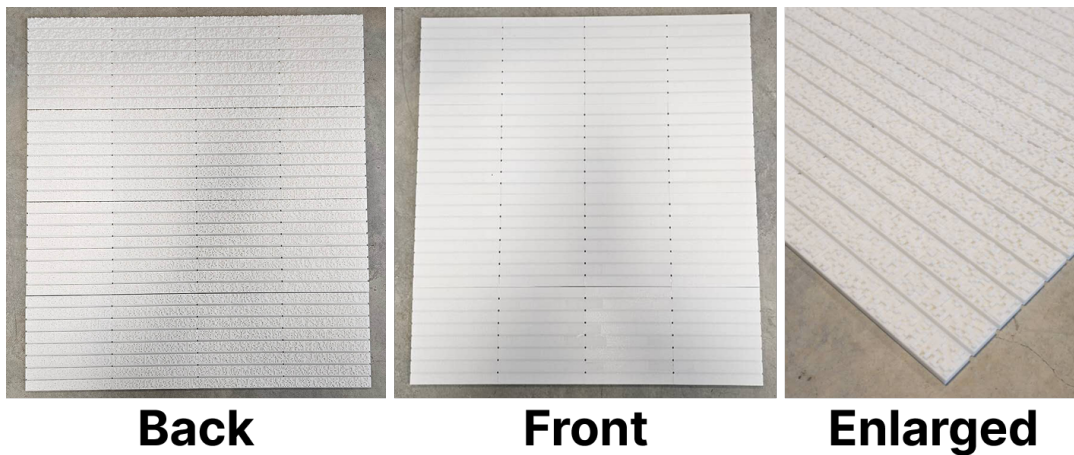


Figure 26: Printed ultra large surface (Sec. F.5). Total material cost is $\approx$ \$40 USD.