AI-driven Metasurface Hyperspectral Imaging

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Hyperspectral Imaging

Standard cameras capture in 3 channels (RGB). Hyperspectral imaging acquires **continuous electromagnetic spectra for every pixel in an image**, creating a **3D spectral cube** of data

HSI in Short-Wave IR (800-1700nm)
1. **Polymers** and **Minerals** have **unique fingerprints in the SWIR** - bond vibrations (C-H, O-H) produce **vibrational overtone bands in the SWIR**
2. Many common dyes are invisible in the SWIR

Material analysis on tapestry – silk (white) and wool (rest)

Current Challenges in HSI

Conventional Hyperspectral Systems

Line Detector | 2D Detector

Dispersive Element | Slit | Filters | Image Mapper

Point Scan | Line Scan | Spectral Scan | Snapshot
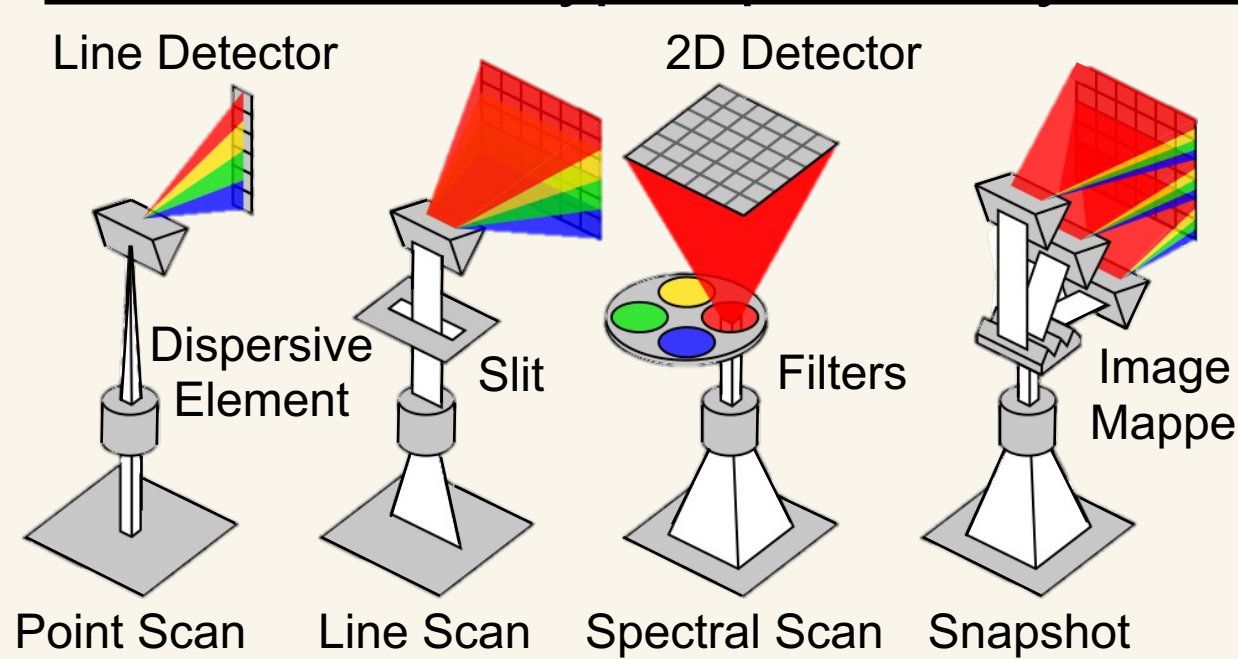
1. Robust Performance
2. Large system volume
3. Slow image recovery

Modern Filter-on-Chip HSI Systems

Compact All-Dielectric Film

Curved variable SiO₂

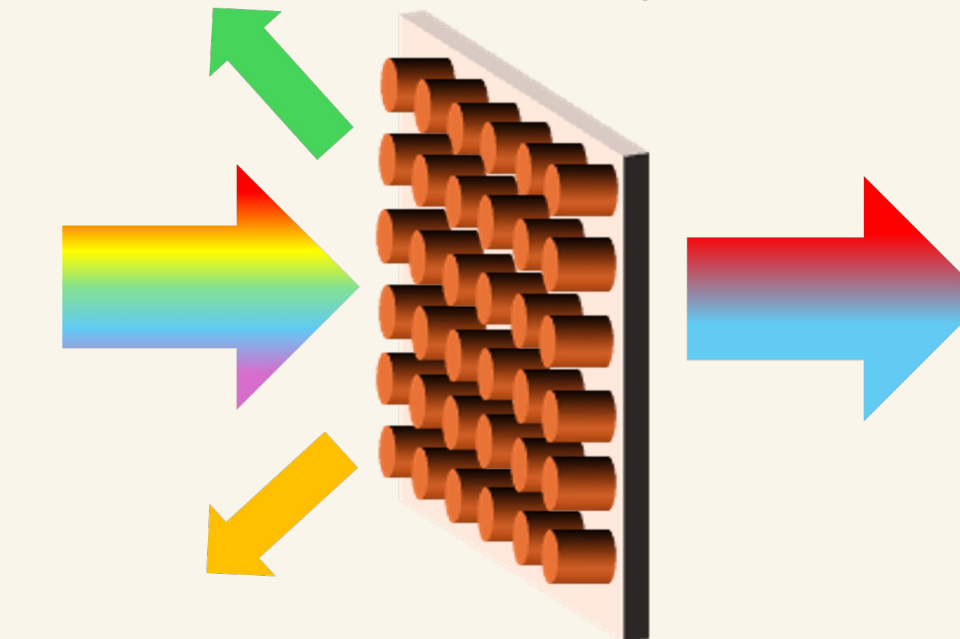Alternating TiO₂ and SiO₂ Layers
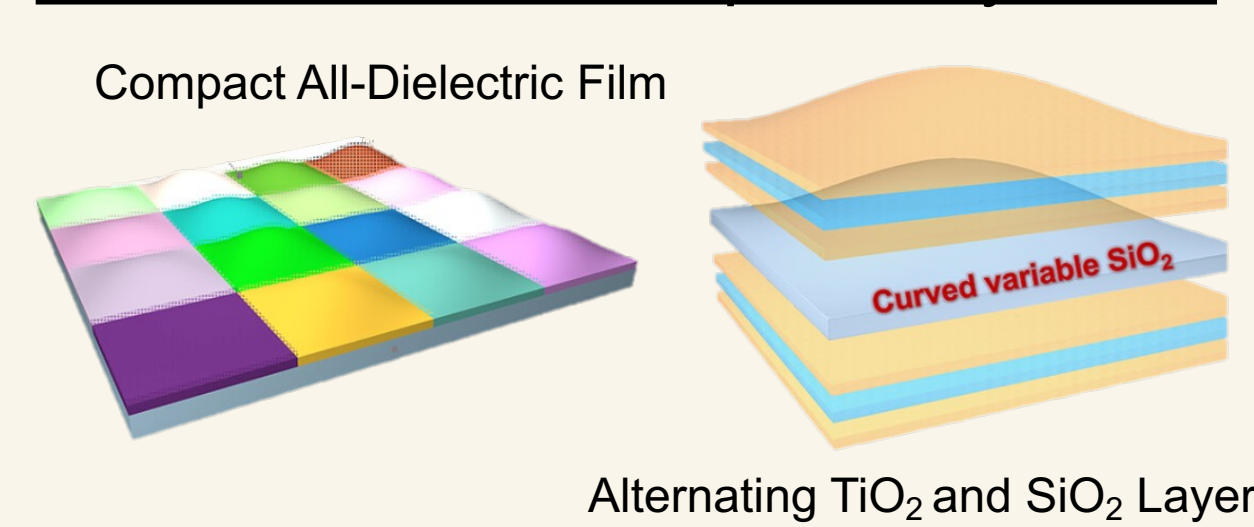
1. Poor angle-robustness
2. Compact
3. Real-time image recovery
4. Complicated fabrication steps
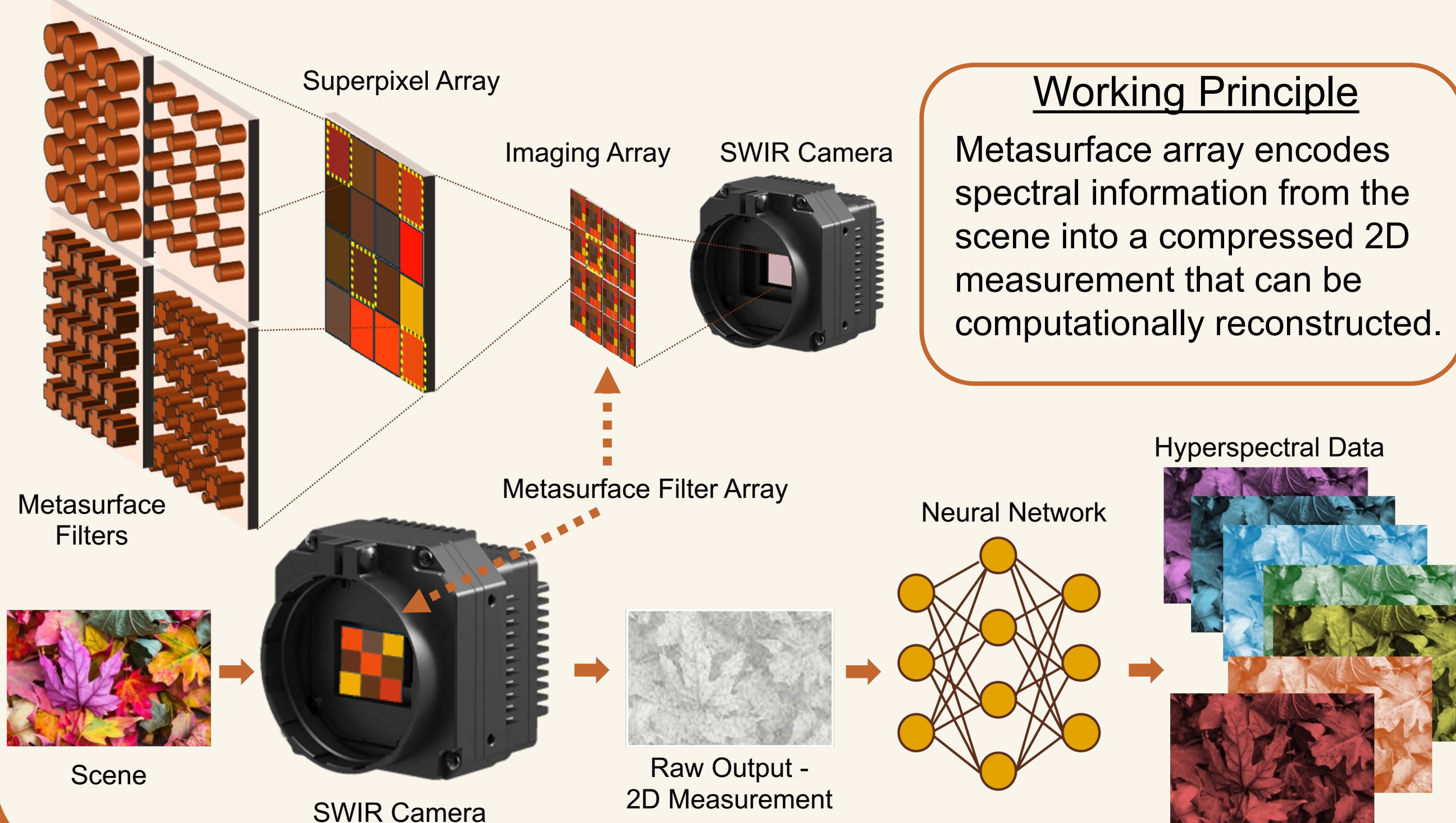
Metasurface Filter Encoders

What are Metasurfaces?
Metasurfaces are flat optics that use subwavelength scatterers to **modulate the amplitude**, phase, and/or polarization of light waves.
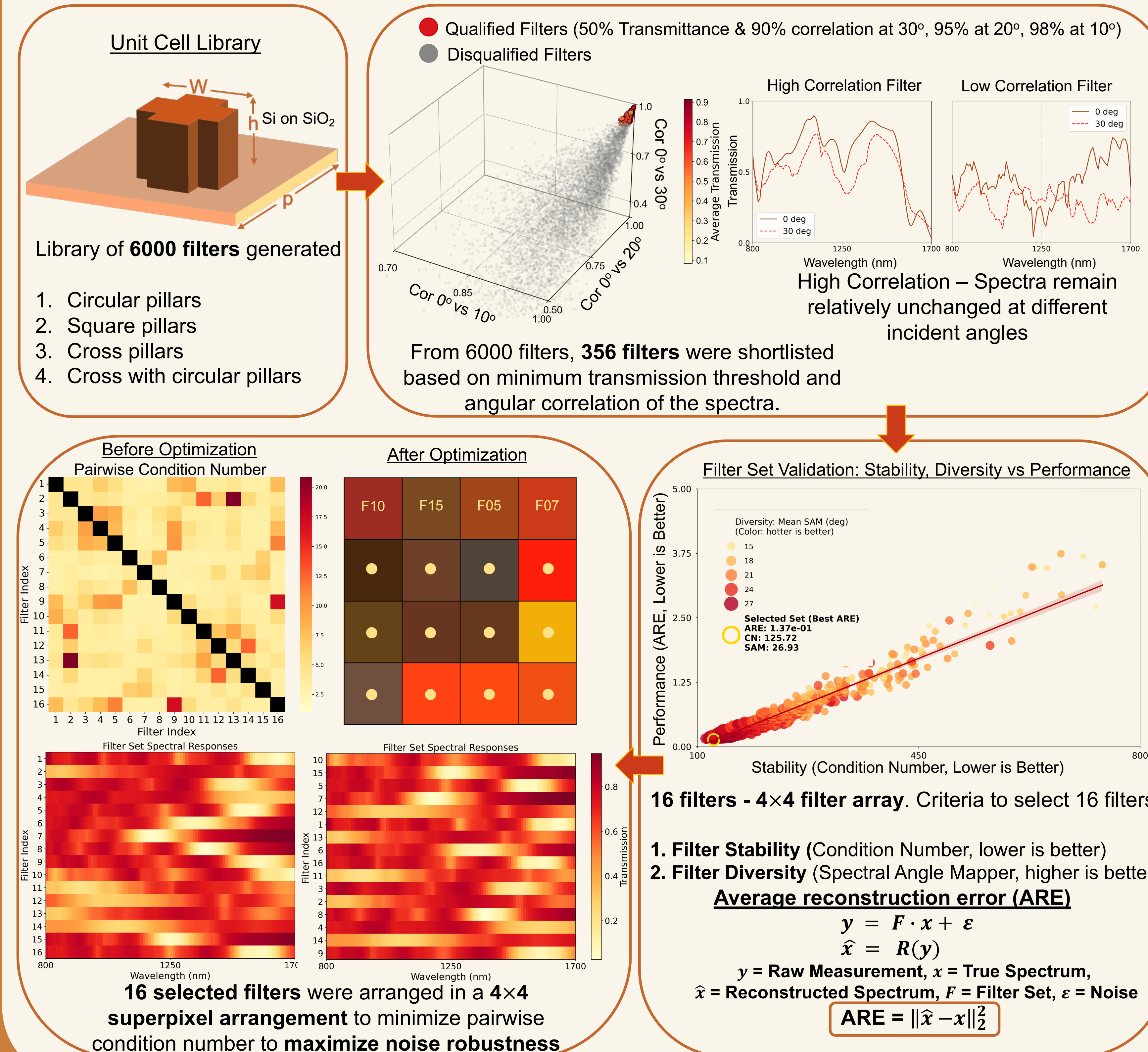
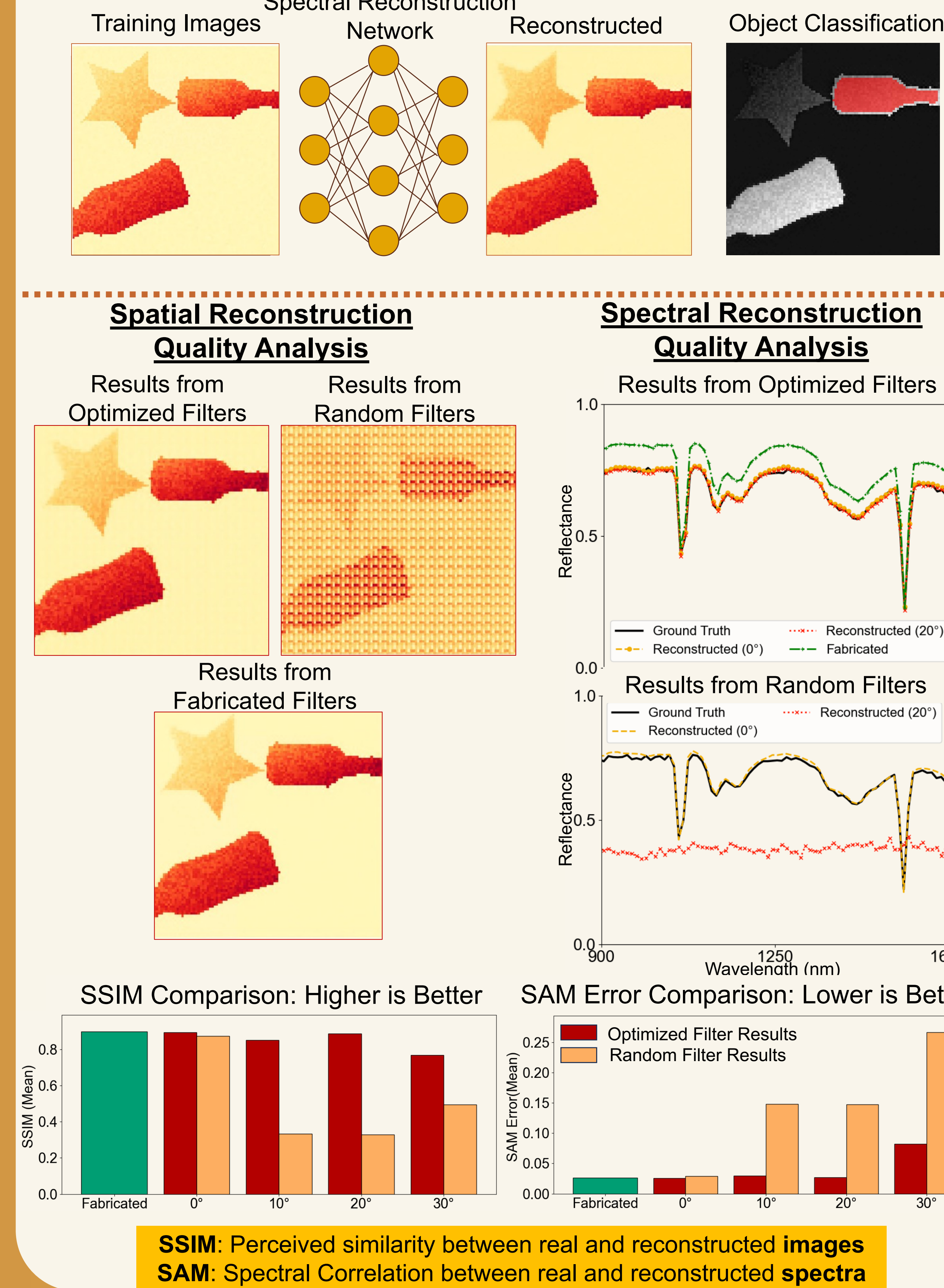Metasurface for Wavelength Control

Developing an angle-robust, high performance hyperspectral reconstruction system using metasurface filter encoders. Simple fabrication involving only a single lithography step.
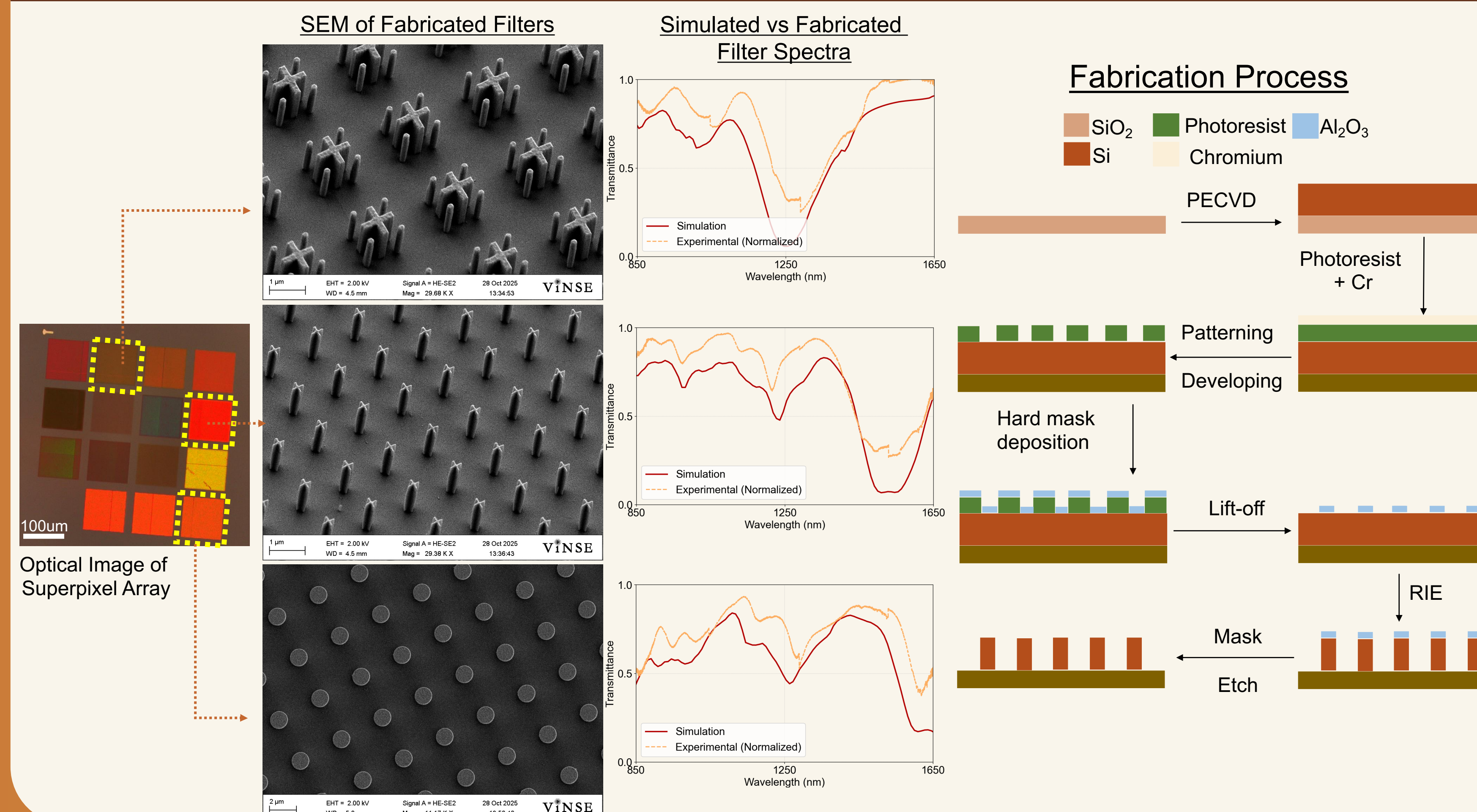
Working Principle
Metasurface array encodes spectral information from the scene into a compressed 2D measurement that can be computationally reconstructed.

Superpixel Array | Imaging Array | SWIR Camera

Metasurface Filters | Metasurface Filter Array | Neural Network | Hyperspectral Data

Scene | SWIR Camera | Raw Output - 2D Measurement

Hybrid Selection Pipeline

Unit Cell Library

Si on SiO₂

Library of **6000 filters** generated

1. Circular pillars
2. Square pillars
3. Cross pillars
4. Cross with circular pillars

● Qualified Filters (50% Transmittance & 90% correlation at 30°, 95% at 20°, 98% at 10°)
● Disqualified Filters

High Correlation Filter | Low Correlation Filter

High Correlation – Spectra remain relatively unchanged at different incident angles

From 6000 filters, **356 filters** were shortlisted based on minimum transmission threshold and angular correlation of the spectra.

Before Optimization — Pairwise Condition Number | After Optimization

F10 | F15 | F05 | F07

Filter Set Spectral Responses

Filter Set Validation: Stability, Diversity vs Performance

Selected Set (Best ARE):
ARE: 1.37e-01
CN: 125.72
SAM: 26.93

16 selected filters were arranged in a **4×4 superpixel arrangement** to minimize pairwise condition number to **maximize noise robustness**

16 filters - 4×4 filter array. Criteria to select 16 filters:

1. Filter Stability (Condition Number, lower is better)
2. Filter Diversity (Spectral Angle Mapper, higher is better)

Average reconstruction error (ARE)

$$y = F \cdot x + \varepsilon$$
$$\hat{x} = R(y)$$

y = Raw Measurement, x = True Spectrum,
$\hat{x}$ = Reconstructed Spectrum, F = Filter Set, ε = Noise

$$ARE = \|\hat{x} - x\|_2^2$$

From Simulation to Fabrication

SEM of Fabricated Filters | Simulated vs Fabricated Filter Spectra

Fabrication Process

SiO₂ | Photoresist | Si | Chromium | Al₂O₃

PECVD

Photoresist + Cr

Patterning

Developing

Hard mask deposition

Lift-off

RIE

Mask

Etch

Optical Image of Superpixel Array

Simulation | Experimental (Normalized)

System Performance

Training Images | Spectral Reconstruction Network | Reconstructed | Object Classification

Spatial Reconstruction Quality Analysis

Results from Optimized Filters | Results from Random Filters

Results from Fabricated Filters

Spectral Reconstruction Quality Analysis

Results from Optimized Filters

Ground Truth | Reconstructed (0°) | Reconstructed (20°) | Fabricated

Results from Random Filters

Ground Truth | Reconstructed (0°) | Reconstructed (20°)

SSIM Comparison: Higher is Better | SAM Error Comparison: Lower is Better

Optimized Filter Results | Random Filter Results

SSIM: Perceived similarity between real and reconstructed **images**
SAM: Spectral Correlation between real and reconstructed **spectra**
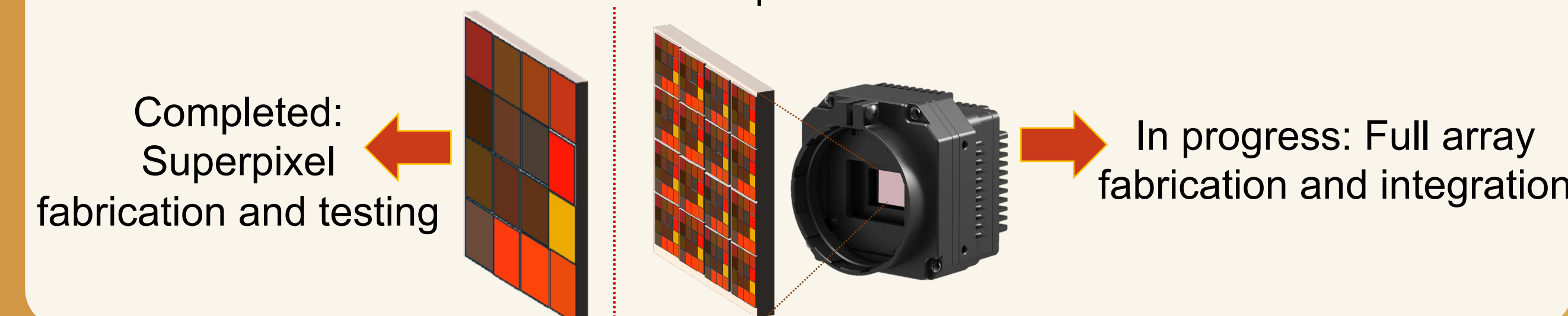
Conclusion and Future Work

1. Developed AI-based hyperspectral reconstruction network
2. Developed a hybrid optimization pipeline to select high performance metasurface filters
3. Fabricated and tested filters to validate performance

Completed: Superpixel fabrication and testing

In progress: Full array fabrication and integration

References and Acknowledgements

1. Shi, W. et al. *ACS Photonics* 2025, 12, 1448.
2. Lucasbosch, CC BY-SA 4.0, via Wikimedia Commons
3. SPECIM – SWIR Manual