

Inverse Design of Phase-Change Metasurface for Single-Pixel Hyperspectral Imaging

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Abstract: We propose a mechanical-scanning-free single-pixel hyperspectral imaging framework using a phase-change metasurface. A differentiable metasurface surrogate model enables joint optimization with a reconstruction network, improving hyperspectral reconstruction fidelity.

1. Introduction

Hyperspectral imaging (HSI) captures rich spectral information at each spatial location and has wide applications in material identification, biomedical imaging, and remote sensing [1,2]. Single-pixel imaging provides a compact alternative by reconstructing high-dimensional scenes from coded measurements acquired by a single detector. However, spectral encoding remains a key challenge for single-pixel HSI, as many existing approaches rely on mechanically switched filters or dispersive components, limiting system compactness and scalability [3,4].

In this work, we propose a phase-change metasurface-based single-pixel HSI framework with end-to-end differentiable optimization. The tunable optical responses of the phase-change metasurface enable spectral modulation without mechanical scanning, allowing a compact imaging architecture [5]. A differentiable metasurface surrogate model, constructed using spline interpolation, is embedded into the single-pixel forward model and jointly optimized with a reconstruction network, enabling task-driven design of the spectral encoder and improving hyperspectral reconstruction fidelity.

2. Method

The framework of the proposed single-pixel HSI system is illustrated in Fig. 1. A hyperspectral scene is first spatially modulated by a digital micromirror device (DMD), after which the modulated light is spectrally encoded by a phase-change metasurface and measured by a single-pixel detector. The resulting measurements are then used to reconstruct the hyperspectral datacube using a neural reconstruction network.

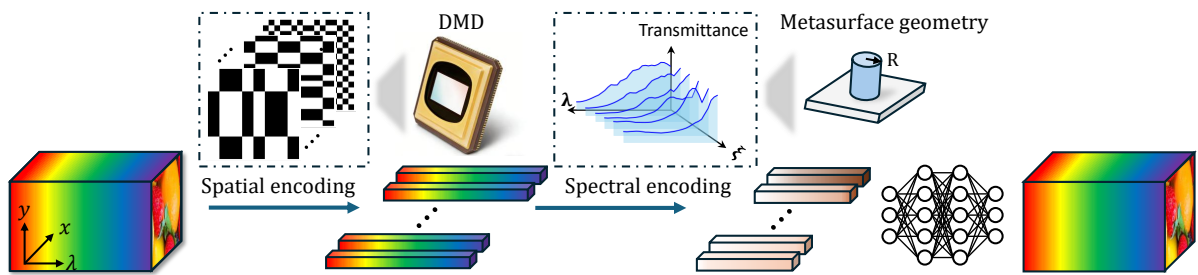


Fig. 1. Overview of the proposed metasurface-enabled single-pixel hyperspectral imaging system.

The measurement process can be written as

$$\mathbf{Y} = \mathbf{H}\mathbf{X}\mathbf{F} + \mathbf{N}, \quad (1)$$

where $\mathbf{X} \in \mathbb{R}^{M^2 \times C}$ denotes the hyperspectral datacube with $M \times M$ spatial pixels and C spectral bands, $\mathbf{H} \in \mathbb{R}^{P \times M^2}$ is the spatial modulation matrix implemented by the DMD, $\mathbf{F} \in \mathbb{R}^{C \times Q}$ represents the spectral encoding matrix determined by the metasurface responses, and $\mathbf{N}$ denotes measurement noise.

Spectral encoding is realized using a phase-change Sb_2S_3 metasurface whose refractive index can be tuned by optical pulses that control the crystallization fraction ξ . The effective permittivity of partially crystallized Sb_2S_3

follows the effective medium theory

$$\frac{\varepsilon(\lambda, \xi) - 1}{\varepsilon(\lambda, \xi) + 2} = \xi \frac{\varepsilon_c(\lambda) - 1}{\varepsilon_c(\lambda) + 2} + (1 - \xi) \frac{\varepsilon_a(\lambda) - 1}{\varepsilon_a(\lambda) + 2}. \quad (2)$$

Six representative crystallization states $\xi = 0, 0.2, 0.4, 0.6, 0.8, 1$ are used as spectral encoding channels, corresponding to a spectral compression ratio of $6/31 \approx 19.4\%$. For spatial encoding, cutting-cake Hadamard basis patterns are adopted with a spatial compression ratio of 50%, leading to an overall compression ratio of 9.7%.

To enable task-driven optical design, a differentiable surrogate model is constructed to map the metasurface structural parameter (radius R) to the spectral responses under different crystallization states. The model is obtained via spline interpolation of full-wave simulated spectra, providing a continuous mapping between metasurface geometry and optical modulation. This differentiable representation allows the metasurface parameter and the reconstruction network to be jointly optimized by minimizing

$$(\hat{R}, \hat{\theta}) = \arg \min_{R, \theta} \|\mathbf{X} - \mathcal{D}_{\theta}(\mathbf{H}\mathbf{X}\mathbf{F}(R))\|_2^2, \quad (3)$$

where $\mathcal{D}_{\theta}(\cdot)$ denotes the reconstruction network with parameters θ .

3. Result

We evaluate the proposed system on the ICVL hyperspectral dataset. On the entire test set, the method achieves an average peak signal-to-noise ratio (PSNR) of 39.35dB and a structural similarity index (SSIM) of 0.9761, indicating high-fidelity hyperspectral reconstruction under compressed measurements.

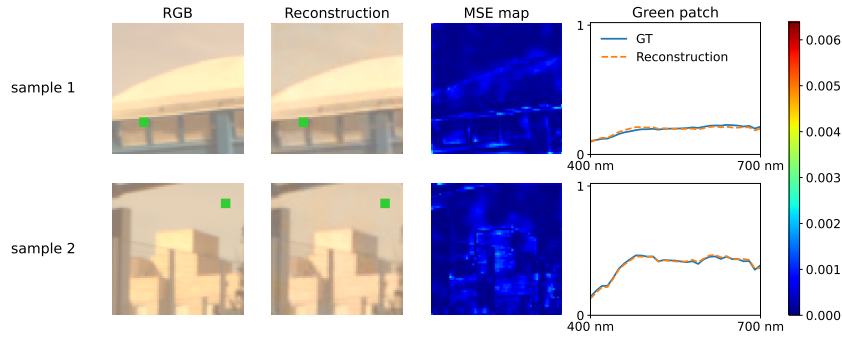


Fig. 2. Two samples reconstructed by the proposed single-pixel HSI system, showing the RGB visualization, MSE map, and spectral comparison at the selected pixel.

Fig. 2 shows two representative reconstruction examples. The reconstructed RGB images closely match the ground truth in both color and spatial structure, while the MSE maps indicate low reconstruction error across the scene. The spectral profiles at the selected pixels also show strong agreement between the reconstructed and ground-truth spectra across the visible range, demonstrating that the proposed framework preserves both spatial and spectral information effectively.

These results demonstrate that the metasurface-enabled single-pixel hyperspectral imaging system, combined with the differentiable optical-computational co-design framework, can achieve accurate hyperspectral reconstruction with compact hardware and without mechanical spectral scanning.

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