

Holography-based 4D computational imaging spectrometer

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Abstract: We present a low-cost, compact 4D dual-shot imaging system called HoloSpec that requires no precisely customized components. It decodes 3D data over 430 spectral channels with high resolution, enabling high-throughput 4D acquisition. © 2026 The Author(s)

1. Introduction

Multidimensional optical imaging aims to capture several information axes in a single dataset [1]. Hyperspectral imaging records a two-dimensional (2D) image with a spectrum at each pixel, enabling material identification via spectral fingerprints and supporting applications from remote sensing to biomedicine and food inspection [2]. Existing spectral imaging systems face persistent trade-offs. Scanning approaches provide strong spectral accuracy but require sequential capture and moving parts, limiting speed and portability. Snapshot methods using filter arrays or coded masks accelerate acquisition, but often reduce spatial/spectral resolution and demand precise fabrication and alignment. Moreover, most systems are intensity-only and discard optical phase, which is valuable for transparent samples and depth-resolved reconstruction [3]. Digital holography can recover phase by recording interference patterns and computationally reconstructing the complex field, enabling 3D imaging with standard sensors [4]. However, holographic systems typically lack high spectral resolution for hyperspectral 4D measurements.

We develop a dispersion-based computational holographic 4D imaging method that avoids coded apertures and filter arrays. A single prism and a monochrome CMOS sensor disperse broadband holograms, while reconstruction uses wavelength-dependent back-propagation with dispersion mapping. Spectral sampling is mainly set by sensor pixels and the prism-sensor distance, and the usable band is determined by sensor response. Experiments decode 430 spectral channels over a 500 nm span with a theoretical 0.3 nm resolution, enabling compact, low-cost, high-throughput holographic 4D acquisition.

2. Methods and experiments

Our system setup is shown in Fig. 1, a 532 nm continuous wave laser and parallel light from a continuous spectrum LED are combined via a beam splitter and directed onto the sample. Following refraction by the prism, the resultant overlapping dispersive image and hologram are captured by a detector.

Under parallel LED illumination, the dispersion diagram observed following refraction through a prism can be interpreted as a linear superposition of discrete monochromatic refraction maps of the sample. The broadband dispersion image I can be treated as the sum of all spectrum components, written as:

$$I = \int \omega(\lambda) U_{\lambda} d\lambda, \quad (1)$$

where the monochromatic images U_{λ} can be mapped once the corresponding position and sample U is obtained. Consequently, images transmitted at varying wavelengths are spatially separated by the prism and subsequently detected by a sensor I , which is indicated in Equation 1. The intensity $\omega(\lambda)$ of each monochromatic map U_{λ} is a function of the sample's transmission coefficients at different wavelengths, effectively representing the transmission spectrum of the sample. We can reconstruct 3D information U of the sample by back-propagating the hologram. According to Snell's Law, the refraction angle, which determines the position of each monochromatic image U_{λ} , is dictated by the prism's varying refractive indices n_{λ} for different wavelengths λ . Based on these principles, we can efficiently detect the spectral lines corresponding to all samples within the same frame by solving Equation 1 using a multiple linear regression (MLR) scheme.

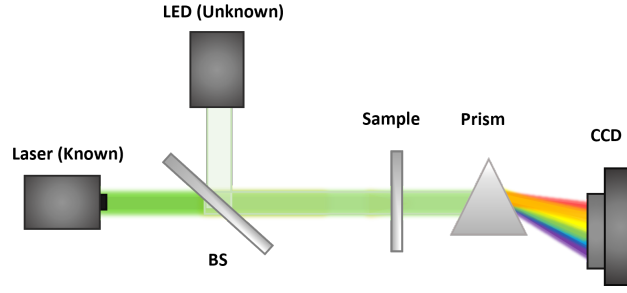


Fig. 1. Setup for our holography-based spectral imaging system.

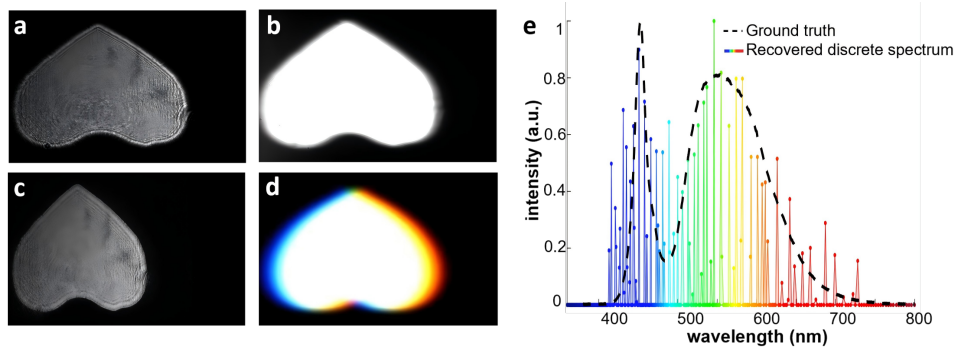


Fig. 2. Decoding progress of our system. (a) Raw hologram. (b) Raw broadband dispersive image. (c) Back-propagated hologram. (d) Recovered dispersive image. (e) Reconstructed 430 discrete spectral values.

3. Results and discussion

In the experiment, monochromatic holograms were initially captured at a wavelength of 532 nm (Fig. 2(a)). Through the process of back-propagation, the 3D spatial information of the sample was determined (Fig. 2(c)). Subsequently, a mathematical model was employed to predict the imaging distribution of the sample on the detector at various wavelengths. Broadband dispersion image I with 500 nm bandwidth spectrum was acquired under white light illumination (Fig. 2(b)), which served as the spectral response variable. The power spectrum $\omega(\lambda)$ at 430 discrete wavelengths was computed using a multiple linear regression (MLR) scheme to solve Eq. 1. The reconstructed spectral curve of the broadband light source is shown in Fig. 2(e). The calculated power spectrum distribution aligned closely with the measured results, even when specified step changes occurred in the power spectrum. The simulated broadband dispersion was reconstructed by multiplying the computed spectral components with the stack of refractive images at the corresponding 430 wavelengths (Figure 2(d)). The reconstructed diffraction patterns closely matched the measured broadband diffraction.

This system enables compact, low-cost dual-shot 4D imaging using a single prism and computational reconstruction, achieving high resolution. Experimental results demonstrate the system's ability to decode 430 discrete frequency responses within a bandwidth of approximately 500 nm, utilizing a dispersion shift of 0.8 mm. Its main limitations are the requirement of two snapshots and that only one spectral line can be decoded per sample, which future PSF design and learning-based single-shot separation aim to address.

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