

Ultra-thin meta-platform for vectorial holography

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Holography is an optical technique that records and reconstructs the light wavefront to generate desired images, emerging as a promising candidate for various display applications. The development of holography has been closely associated with computer-generated holography, in which the discretized phase and amplitude distributions of electromagnetic waves are computationally calculated and physically implemented using optical devices such as spatial light modulators and diffractive optical elements. In parallel, a variety of iterative phase retrieval algorithms, most notably the Gerchberg–Saxton (GS) algorithm, have also been studied to improve the fidelity and accuracy of the hologram reconstruction.^{1,2} Despite these advances, conventional implementations suffer from intrinsic limitations such as undesired higher-order diffraction, low spatial resolution, restricted viewing angles, and system bulkiness. Recently, metasurfaces, ultra-thin planar optical elements composed of artificially arranged subwavelength-scale structures, have garnered significant attention for holographic applications as a promising route to overcome the limitations of conventional holographic systems.^{3,4} Numerous studies have utilized metaholograms for next-generation holographic devices, including three-dimensional displays,^{5,6} optical encryption,^{7–9} and augmented/virtual reality (AR/VR) systems.^{10,11} However, many studies on metaholograms have primarily focused on scalar holography, without fully exploiting the vectorial nature of light. In most cases, holographic images have been typically generated with uniform polarization distributions. Some studies have demonstrated multiplexing of the metahologram responses under two orthogonal polarization bases,^{12,13} however, such approaches generally switch between two scalar optical wavefronts rather than enabling vectorial images with arbitrarily varying polarization distributions.

In recent years, the generation of vectorial holograms with metasurfaces has also been increasingly investigated, enabling the control over the polarization distributions in the far-field patterns.^{14–18} Nevertheless, a general methodology for designing vectorial metaholograms, capable of generating arbitrary vectorial fields while simultaneously achieving high efficiency, remains an outstanding challenge. Recently, Liu et al. proposed vectorial holography based on metasurfaces with single-structure meta-atoms generating arbitrary polarization distributions, as shown in Fig. 1(a).¹⁹ Their method integrates the GS algorithm with a wave decomposition technique, retrieving the optical properties necessary for producing desired vectorial holographic images. To obtain the near-field scattering properties corresponding to the far-field vectorial image, the target far-field is first decomposed into two orthogonal circular polarization bases. The GS algorithm is then applied to retrieve the near-field sources for each polarization component. By taking a coherent linear superposition of the two retrieved near-field planar sources, the final near-field distribution is obtained, which enables the realization of the target Jones matrix for the metasurface design.

The metasurface is designed based on single-structure meta-atoms employing metal–insulator–metal (MIM) configuration with a metallic cross resonator on the top layer. In this design, each length of the orthogonal bars of the cross structure is adjusted to control the resonance phase and the cross-polarization phase difference. By introducing the rotation angle as an additional design parameter, three independent degrees of freedom are available, providing comprehensive control over the near-field properties for generating arbitrary far-field polarization distributions. Importantly, this approach offers broader design flexibility compared with previous designs with unrotated single-nanorod-based structures, which have inherent restrictions in their ability to manipulate the vectorial fields. Furthermore, the other geometrical parameters of the MIM structures are carefully optimized to ensure broad phase coverage and high reflection amplitudes, which contributes to the realization of high-efficiency devices.

The versatility of the design approach is demonstrated through several types of vectorial holograms at the wavelength of 1064 nm. First, Liu et al. design metasurfaces capable of generating identical vectorial holographic images under different incident polarization states, showing that the design method can operate for arbitrary incident polarizations. In another demonstration, metasurfaces are designed and fabricated to produce vectorial holographic images with and without rotational symmetries. For the more general case without rotational symmetry, three different metasurfaces are designed to generate distinct vectorial images of a vectorial clock, flower, and flying bird, each exhibiting both complex intensity and polarization distributions [Fig. 1(b)]. The metasurfaces are designed to produce the target vectorial images under the left-circularly polarized (LCP) incidence. When illuminated by LCP incident light, the generated holographic images show good agreement with the target images. Polarization analysis using a rotatable polarizer as an analyzer in front of the charge-coupled device (CCD) further confirmed the vectorial property of the images because the linear polarization components orthogonal to the analyzer angle are suppressed as the polarizer is rotated, whereas the circular polarization components remained unaffected. In addition, the metasurface platform achieved a high working efficiency of 67.9%, which represents an improvement over previous metasurface-based vectorial holography approaches.

In summary, Liu et al. propose an effective design strategy for generating arbitrary vectorial holography with an ultra-thin metasurface platform and demonstrate its applicability with different versatile vectorial images.¹⁹ This approach can be further expanded to a transmissive system using a dielectric metasurface, which can potentially achieve higher efficiency devices. Furthermore, integrating this platform with active materials such as liquid crystals could enable dynamic operation and broaden its applicability. As the demand for compact and efficient holographic devices continues to increase, metasurface-based platforms for vectorial holography are expected to receive greater attention. This work opens new opportunities for controlling a wider range of light properties through vectorial holography, paving the way for practical applications including photonic encryption, optical cryptography, and anti-counterfeiting technologies.

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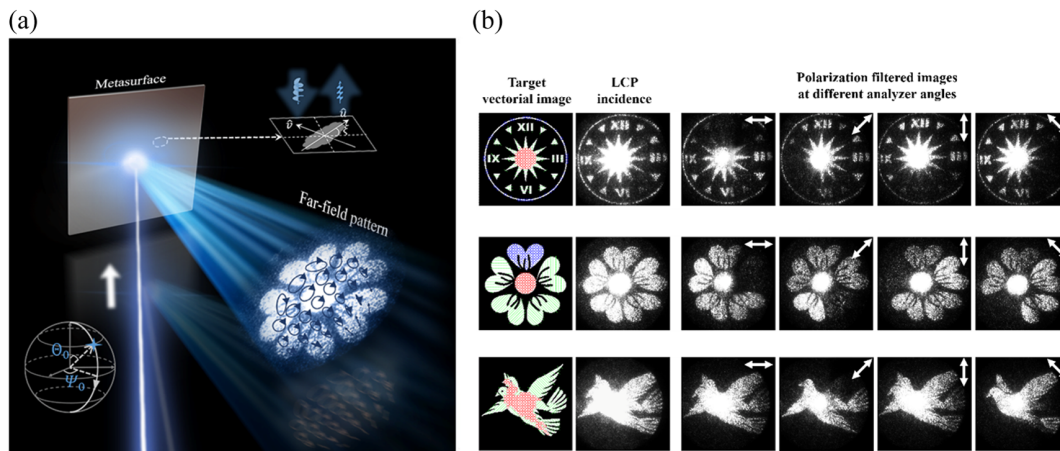


Fig. 1 (a) Schematic illustration of vectorial holography using an ultra-thin metasurface platform. (b) Experimental images of vectorial holography generated by the metasurface. In the target vectorial images, different polarization distributions are encoded, where red and blue circles denote left and right circular polarizations, and green segments indicate linear polarizations (adapted from Ref. 19).

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