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Hybrid metasurfaces-freeform optics bring multi-depth AR close to reality

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Abstract: Achieving realistic depth perception in augmented reality (AR) displays remains a central challenge due to the reliance on single focal planes. In the recent work published in *Opto-Electronic Science*, researchers from Beijing Institute of Technology and their collaborators report a hybrid metasurface-freeform optical architecture that enables simultaneous multi-focal plane display within a compact, solid-state system. By combining polarization-multiplexed metasurfaces with freeform optics through a joint design framework, the system generates multiple depth cues without time multiplexing and remains compatible with practical display hardware. This work highlights a promising route toward cross-scale optical co-design for realistic near-eye display systems.

Keywords: multi-depth AR display; metasurface-freeform; joint design; non-orthogonal polarization multiplexing

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Augmented reality (AR) displays have long promised a seamless fusion of digital information with the physical world, yet delivering comfortable and realistic three-dimensional (3D) perception in a compact wearable form remains elusive[1,2]. A key limitation of current systems is the reliance on single focal planes, which inevitably leads to accommodation-vergence conflict and visual fatigue during prolonged use[3]. While multiple approaches have been explored to introduce depth cues, reconciling optical performance, system compactness, and practical implementation continues to be a nontrivial challenge[4,5].

In a recent work, Wang, Yang, Huang and their collaborators report a hybrid metasurface-freeform optical architecture that enables multi-focal plane AR display within a compact, solid-state system[6]. By integrating a polarization-multiplexing metasurface, freeform optical elements, and an OLED microdisplay, the authors demonstrate a system capable of generating virtual images at multiple depths (0.7 m, 1.5 m, and 3 m) simultaneously, as shown in Fig. 1. This represents a meaningful step toward addressing the long-standing depth rendering problem in near-eye displays.

The key idea lies in combining two complementary optical paradigms. Metasurfaces offer subwavelength control of wavefronts and enable multifunctional phase encoding within a single planar element[7,8], while freeform optics provide the degrees of freedom required to correct aberrations in highly asymmetric and off-axis configurations[9]. Rather than treating these components independently and pursuing extreme functionality at either the wave-optics or geometric-optics level alone, the work adopts a joint design strategy and highlights the importance of co-design across scales, in which the metasurface is incorporated into a ray-tracing framework as an effective phase function. This approximation significantly reduces computational complexity while still capturing the essential system-level behaviour.

A particularly interesting aspect is the use of non-orthogonal polarization multiplexing to encode multiple phase profiles within a single metasurface. Different regions of the display are assigned distinct polarization states, which are then mapped to different virtual image distances after modulation. This approach avoids time multiplexing or mechanically tunable elements, both of which typically introduce additional system complexity or latency. At the same time, the resultant crosstalk between polarization channels and impact on the accuracy of phase reconstruction

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are partially addressed through careful metasurface design and optimization.

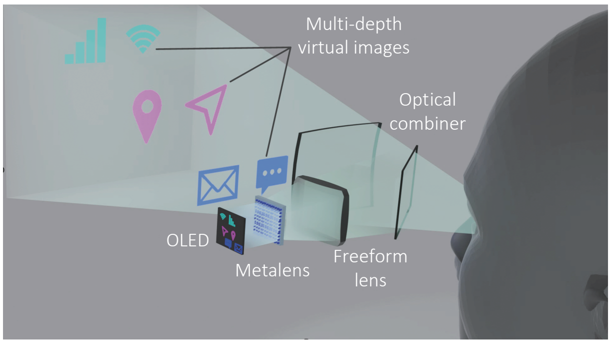

Fig. 1 | Illustration of the reported multi-focal plane AR display system[6].

Compared with existing AR display strategies, this hybrid approach occupies pragmatic middle ground. Conventional geometric optical solutions often rely on multiple optical paths or stacked modules, resulting in increased system volume and alignment difficulty. In contrast, holographic or SLM-based methods provide fine depth control but suffer from limited efficiency, high computational cost, and compatibility issues with practical display hardware[10]. By leveraging metasurfaces for multiplexed wavefront control while maintaining compatibility with amplitude-modulated displays, this work highlights the importance of co-design across optical scales.

The experimental prototype further substantiates the concept. Clear depth-dependent imaging is observed across multiple focal planes, with digital content appearing in focus at its designated distance and defocusing elsewhere —an essential requirement for correct accommodation cues. More broadly, this work points toward hybrid optical systems in which functionality is distributed across scales: subwavelength metasurfaces handle local wavefront shaping and multiplexing, while macroscopic freeform optics manage imaging, relay, and system integration. Such cross-scale co-design is likely to become increasingly important as optical systems grow in complexity.

Further progress will depend on advances in several directions. On the device side, improving metasurface efficiency, bandwidth, and fabrication scalability remains critical, particularly for full-colour operation. At the system level, more accurate yet efficient modeling frameworks —potentially incorporating inverse design or physics-informed learning —could further enhance integration between diffractive and refractive components. Consideration of display characteristics, including pixel architecture and polarization management, will also be essential as part of the overall design space. Nonetheless, this approach offers a promising route toward compact, multi-depth AR displays with improved visual realism.

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