Nanophotonics and AI for Augmented Reality and Imaging Applications

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Abstract

We present fundamental principles and applications of metasurfaces with a particular focus on AR displays that integrate nanophotonic waveguides and AI-driven holography to achieve full-color 3D holographic AR. Key technologies include inverse design, nanofabrication, and AI-driven algorithms. We will also discuss remaining challenges and our perspectives on advancing next-generation systems.

Author Keywords

Augmented and virtual Reality, Near-eye displays, Holographic displays, 3D displays, Computer-generated holography, Nanophotonics, Nanofabrication, Metasurfaces, Meta-optics, Artificial intelligence, Computational imaging.

1. Introduction

Emerging technologies in optics and photonics are driving transformative advancements in next-generation displays, such as virtual reality (VR) and augmented reality (AR) near-eye displays. These innovations enable immersive experiences across diverse domains, including entertainment, education, communication, and training [1, 2]. However, existing AR/VR displays face critical challenges from the limitations of conventional optical elements, such as refractive and diffractive optics. To achieve widespread adoption, AR/VR devices must address constraints related to compactness, visual quality, 3D capabilities, and energy efficiency. Unfortunately, traditional optical designs are inherently bulky or lack the advanced light manipulation capabilities required for high optical performance systems, hindering their integration into compact and practical near-eye devices. These limitations negatively affect both device portability and the overall visual experience for users. Hence, a new optical element solution is required to address these challenges.

Metasurfaces, which are planar optical elements composed of two-dimensional arrays of nanostructures, offer a promising solution to these challenges. Metasurfaces enable unprecedented manipulation of light amplitude, phase, polarization, and spectrum at the nanoscale within an ultrathin form factor [3-5]. This unique combination of miniaturization and enhanced functionality positions metasurface optical elements as promising alternatives to conventional optics [6-8], providing opportunities to revolutionize AR/VR near-eye display technologies.

This talk introduces the current status of AR/VR near-eye displays with their current limitations and highlights two key applications of metasurfaces as solutions: (1) metasurface lenses for wide field of view AR displays [9] and (2) metasurface waveguides for full-color 3D holographic AR [10]. We will present the motivation, principles, and experimental results of our recent achievements in metasurface-based AR displays, followed by a discussion of remaining challenges and future research directions, offering our perspectives on advancing next-generation optical systems.

2. Metalenses for Wide-field-of-view AR displays

Achieving a wide field of view (FOV) in AR displays is essential for immersive experiences. However, existing AR systems face significant challenges in delivering a wide FOV without compromising device compactness and user experience. Current AR displays rely on bulky combiner optics (e.g., beam splitters, curved mirrors, and freeform optics) coupled with eyepiece lenses to magnify virtual content. These components require substantial separation between the eyepiece and the user's eye to avoid physical interference and optical distortions of the real-world scene, such as blurring. This spatial constraint limits the FOV and increases the system's form factor, hindering portability and immersive AR functionality.

To address these challenges, we propose a single-layer see-through metalens as an eyepiece for AR displays. The see-through metalens is designed with subwavelength nanostructures that provide engineered anisotropic responses, enabling it to simultaneously function as a high-performance imaging lens for virtual content and as transparent glass for the real-world scene. With a high numerical aperture (NA), the metalens ensures efficient light focusing and imaging, achieving short focal lengths and high magnification across broadband RGB wavelengths. By integrating the see-through metalens, the eyepiece can be positioned directly in front of the user's eye, behind the combiner optics. This design significantly enlarges the FOV by magnifying the virtual content with high fidelity while maintaining clear transmission of the real-world scene. The proposed metalens is fabricated using scalable nanoimprint lithography, demonstrating its potential for mass production and commercialization.

Using the fabricated metalens with a 20 mm diameter and 0.61 NA, we experimentally demonstrated a full-color optical see-through AR display with an FOV exceeding 90°. This marks a significant improvement over the FOV achievable with conventional AR systems. Chromatic aberrations inherent to metalenses were mitigated through dispersive optical path length compensation via system engineering, enabling high-quality full-color AR imaging. These results underscore the potential of metasurface lenses for integration into AR near-eye displays, offering a more immersive user experience with a wide FOV.

3. Metasurface waveguides for full-color 3D holographic AR displays

Achieving realistic 3D representation in AR displays is crucial for addressing the vergence–accommodation conflict, a primary

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cause of visual discomfort in conventional near-eye displays. Most existing AR systems rely on bulky projection optics and are limited to displaying 2D images on a fixed depth plane, which reduces perceptual realism and compromises device portability. While 3D optical display technologies such as light field displays and varifocal displays attempt to create 3D visual experiences for near-eye display platforms, they suffer from limited visual quality, low resolution, constrained depth representation, or bulky system configurations. These limitations make them unsuitable for compact, high-quality 3D AR near-eye displays.

To address these challenges, we propose a novel 3D holographic AR display that combines an inverse-designed metasurface waveguide with AI-driven holography algorithms. The metasurface waveguide is optimized for full-color optical see-through (OST) operation in a compact form factor. Our waveguide system is composed of high-index glass materials and designed to enable precise wavefront propagation through multiple total internal reflections, incorporating metasurface gratings inverse-engineered for high diffraction efficiency and angular uniformity for RGB wavelengths. Further dispersion compensation is achieved through system-level design by momentum matching the input and output couplers, ensuring corrected chromatic aberrations. For generating high-quality computer-generated holograms (CGHs), we develop a physically accurate waveguide model combined with learnable model components trained on experimentally captured datasets. This AI model accounts for physical phenomena, fabrication errors, and practical misalignments in the waveguide system, enabling the generation of full-color, high-quality 3D holograms through the waveguide system.

Our prototype demonstrates unprecedented full-color 3D holographic AR performance with a compact form factor. The metasurface waveguide, fabricated using electron-beam lithography on the high-index glass substrate, achieves high diffraction efficiency and angular uniformity, with high see-through efficiency across the visible spectrum. Experimental results validate the system's capability to produce high-quality 3D holographic images, accurately reproducing defocus behavior thus mitigating visual discomfort. The AI-driven wave propagation model further enhances image fidelity, outperforming conventional free-space and physical-only models by a large margin. These findings highlight the potential of our metasurface waveguide and AI-driven holography for creating immersive and realistic AR experiences with both compactness and high visual quality.

4. Metasurface waveguides for full-color 3D holographic AR displays

Despite these advancements, several challenges remain. Current metasurface designs face fabrication limitations, particularly for large-area devices and their mass production required in commercial applications. Enhancing the scalability of metasurface manufacturing, including advanced lithography and nanoimprint techniques, is crucial. Additionally, improving the étendue of holographic displays and improving both eyebox and FOV will require further integration of novel devices and system architectures. Continued innovation in co-designed optical systems and AI algorithms will be important for realizing practical, next-generation AR/VR platforms. The unique combination of nanophotonics and AI could also be applied to various domains including optical imaging, and our talk will also discuss their potential applications with our perspectives.

In conclusion, metasurfaces and AI offer transformative potential for AR/VR applications, addressing fundamental challenges in optical design while paving the way for compact, efficient, and high-performance AR/VR displays. By bridging nanophotonics and artificial intelligence, these technologies are poised to shape the future of immersive spatial computing systems. Achieving a wide field of view (FOV) in AR displays is essential for immersive experiences. However, existing AR systems face significant challenges in delivering a wide FOV without compromising device compactness and user experience. Current AR displays rely on bulky combiner

5. References

1. Chang C, Bang K, Wetzstein G, Lee B, Gao L, Toward the next-generation VR/AR optics: a review of holographic near-eye displays from a human-centric perspective. Optica 2020;7:1563.
2. Kress BC, Chatterjee I. Waveguide combiners for mixed reality headsets: a nanophotonics design perspective. Nanophotonics (Berlin). 2020;10:41–74.
3. Lee GY, Kim H, Park JH, Lee B. Complete amplitude and phase control of light using broadband holographic metasurfaces. Nanoscale. 2018;10:4237–45.
4. Yu N, Genevet P, Kats MA, Aieta F, Tetienne JP, Capasso F, et al. Light propagation with phase discontinuities: generalized laws of reflection and refraction. Science. 2011;334:333–7.
5. Kuznetsov AI, Miroshnichenko AE, Brongersma ML, Kivshar YS, Luk'yanchuk B. Optically resonant dielectric nanostructures. Science. 2016;354:aag2472.
6. Lee GY, Sung J, Lee B. Metasurface optics for imaging applications. MRS Bull. 2020;45:202–9.
7. Chen WT, Zhu AY, Capasso F. Flat optics with dispersion-engineered metasurfaces. Nat Rev Mater. 2020;5:604–20.
8. Arbabi A, Faraon A. Advances in optical metalenses. Nat Photonics. 2023;17:16–25.
9. Lee GY, Kim H, Lee B, Wetzstein G. Metasurface eyepiece for augmented reality. Nat Commun. 2018;9:4562.
10. Gopakumar M, Lee GY, Choi S, Chao B, Peng Y, Kim J, et al. Full-colour 3D holographic augmented-reality displays with metasurface waveguides. Nature. 2024;629:791–7.