Advancing near-eye light field displays using meta-optics

Jianwen Dong*, Xia Liu*, Wenlong Lu*, Zhibin Fan*, Yang Yi*, Qimeng Wang**, Yifan Ding**, and Zong Qin**

***School of Physics, Sun Yat-Sen University, Guangzhou, China**
****School of Electronics and Information Technology, Sun Yat-Sen University, Guangzhou, China**

Abstract

Near-eye light field displays encounter a limited depth of field (DOF) and narrow FOV due to the low light modulation abilities of the traditional microlens array. This study introduces meta-optics and designs specific phase responses to different polarizations and incident angles. A DOF covering over six diopters and a FOV larger than 40 degrees were experimentally verified.

Author Keywords

Light field display; Meta-optics; Depth of field; Field of view.

1. Introduction

XR display has significantly evolved in resolution, FOV, and compactness thanks to the development of modern optical architectures such as the Pancake and waveguides. However, the vergence-accommodation conflict (VAC) is still a big challenge. The VAC induces severe visual fatigue in VR due to varying binocular parallaxes under a constant image depth. In AR use, things may be worse, as recent studies [1] demonstrated an increased time-to-focus and impaired eye-hand coordination caused by the VAC.

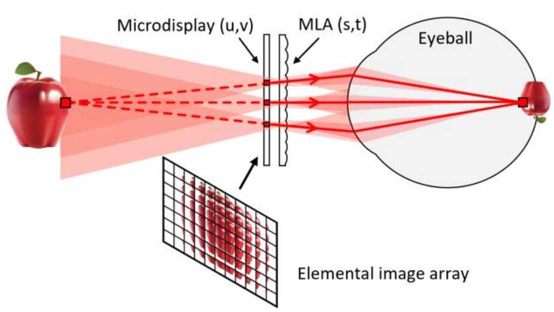

Fig. 1. General architecture of near-eye light field displays

Reconstructing monocular focus cues identical to the real world is essential to alleviate the VAC. To this end, depth-fused display, Maxwellian view display, varifocal display, holographic display, or light field display (LFD) can be used [2,3]. Of them, the LFD provides computational focus cues with a compact volume; no coherent source is required so that LFDs can take advantage of fast-developing micro-displays.

Fig. 1 shows the general architecture of near-eye LFDs. Although the LFD is sometimes considered a reversed path of light field photography through a camera array with depth-dependent parallaxes, this study deems it a reconstruction process of wavefronts. Unlike the holographic display that aims to create a wavefront through diffraction, an LFD adopts a quite different strategy based on its incoherent microdisplay. As Fig. 1 shows, the wavefront from a real object is segmented into wavelets. The visual response to the real object can be accurately reproduced if each wavelet is a perfect segmentation of the entire wavefront. In addition, because the human eyes work based on retinal images in terms of light intensity but not complex amplitude, the wavelets can be mutually incoherent. Therefore, the task of the LFD is to create particular wavelets with pixels on a microdisplay as the sources of the wavelets.

However, the most typical LFD using a microlens array (MLA) intrinsically generates imperfect wavelets. The curvature of the wavefront to be reconstructed varies with the image depth. At the same time, favorably, the LFD can computationally alter the chief rays of the wavelets to be perpendicular to the wavefront. However, the curvature of each wavelet is constantly determined by the MLA's focal length and the microdisplay's object distance to the MLA (i.e., the Gaussian formula). Except for the depth where the curvatures of the wavelets coincide with the reference wavefront (known as the center depth plane, CDP), defocus degrades the retinal image to a certain extent, causing a limited depth of field (DOF). The DOF issue is significantly hindering because LFDs are expected to work as a 3D display.

Besides the DOF issue, another important specification affected by imperfect wavelet generation is the field of view (FOV). Spherical wavelets can be produced in the paraxial regime (the central field). On the other hand, in large fields, wave aberrations of oblique beams through the MLA severely distort the wavelets. Thus, the FOV is limited by the off-axis aberration of the MLA, usually no more than 20 degrees [4].

The common cause underlying the DOF and FOV issues is the MLA's limited freedom in modulating light. Therefore, current studies usually multiplex MLAs with different parameters. For example, [5] designed a dual-focal lens array for DOF extension, and [6] proposed a compound lens array (i.e., multi-element lens) for off-axis aberration suppression. However, such approaches increase the complexity and volume. Moreover, the effort is dedicated to a particular goal (e.g., FOV expansion) but cannot achieve an all-around LFD. Therefore, the LFD area desires a new solution integrating versatile light modulation functions into a monolithic element.

In the meantime, a novel optical element attracts emerging attention as a promising solution for miniaturized optical components, i.e., meta-optics using a subwavelength array of optical antennas to manipulate light in the visible flexibly. In particular, the metasurface has the flexibility of controlling the phase and polarization, as it leverages the distinct phase responses of nanostructures to incident light with different polarizations and angles. Our previous works [7,8] reported near-eye LFDs using a metalens array, demonstrating the feasibility of LFDs based on meta-optics, removing the obstacles to highly flexible light modulation using meta-optics. This study extends our previous ones to propose a near-eye LFD with an extended DOF and expanded FOV, enabled by a newly designed and fabricated metalens array with varying phase responses to different polarizations and incident angles. The DOF can cover over six diopters, and the FOV is more significant than 40 degrees. The following sections briefly introduce our results, and the full text will report detailed design and fabrication methods.

2. Extended depth of field

Current LFDs adopt an MLA with a fixed focal length, preventing them from altering the wavelets. This study proposed and experimentally demonstrated an extended DOF LFD using a polarization-multiplexed (PM) metalens array. The PM metalens array adopts rectangular a-Si nanoposts that create polarization-sensitive phase profiles for orthogonal linear polarizations, as shown in Fig. 2. In this manner, a bifocal metalens array enables two CDPs, one for the personal space close to the user and the other for the vista space. The two CDPs are multiplexed by fast switching the polarization state of a microdisplay. The DOFs of the two CDPs are merged for an overall DOF of over six diopters. Fig. 3 shows the resolution test result across an extensive diopter range.

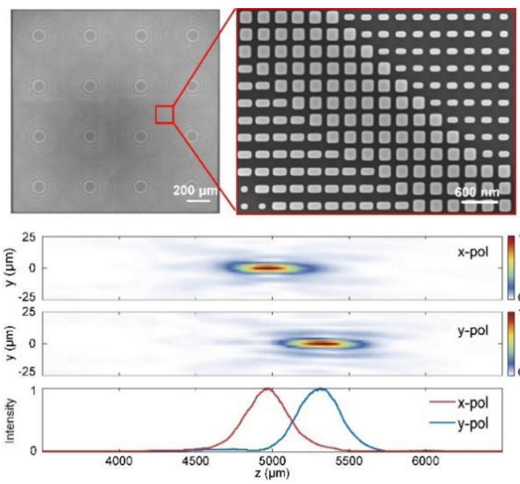

Fig. 2. The PM metalens derive (upper) and the focal length test for x- and y- linearly polarized light.

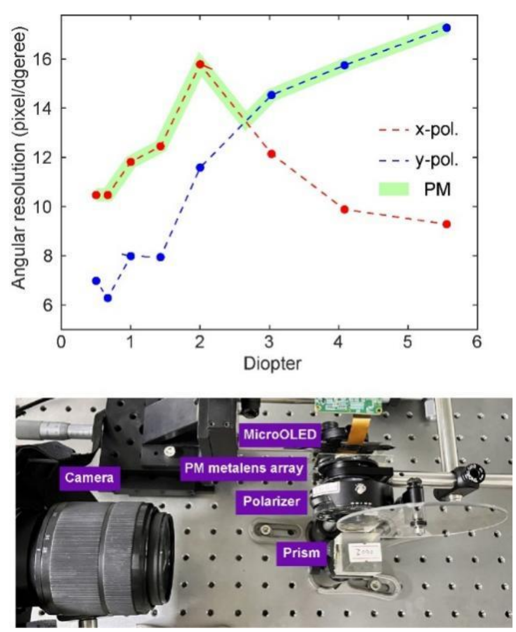

Fig. 3. Upper: resolution (in pixels per degree) as a function of image depot. Lower: Experimental setup for the test.

3. FOV expansion

The narrow FOV of near-eye LFDs comes from the oblique beam at large fields. Thus, we propose a metalens array with a freeform phase response profile, which contains a linear phase term whose inclination varies with the incident angle, as well as a quadratic term for light convergence, as Fig. 4 shows. Though it is not difficult for a traditional lens to be optimized for off-axis fields, integrating the complicated phase profile into a monolithic microlens array while keeping its slim volume is challenging. As a result, we used a commercial camera to test the expanded FOV, as shown in Fig. 5. An FOV larger than 40 degrees was achieved.

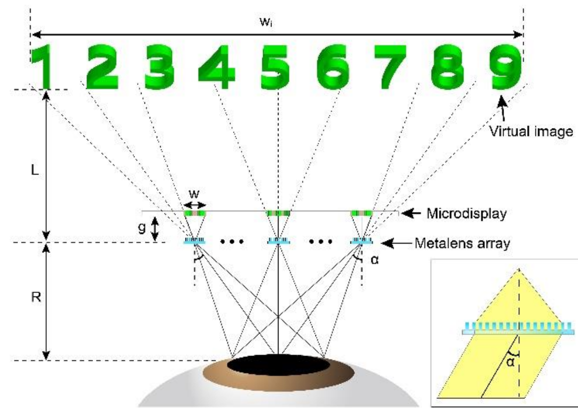

Fig. 4. Metalens array with a freeform phase response profile for FOV expansion: a linear phase term dependent on incident angle and a quadratic term.

Fig. 5. Experimental result of FOV expansion: a 40-degree-FOV confirmed with a commercial camera

4. Conclusions

We developed a new metalens array regarding the DOF and FOV issues of near-eye LFDs. Phase responses dependent on polarizations and incident angle were achieved with the help of the highly flexible modulation ability of meta-optics, removing the intrinsic obstacle of traditional MLAs. As a result, a DOF covering over six diopters and a FOV larger than 40 degrees were experimentally verified.

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