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Special Topic: Metasurfaces of Novel Designs and Functionalities

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New opportunities for metalenses in imaging applications

Tao Li*

National Laboratory of Solid State Microstructures, College of Engineering and Applied Sciences, Nanjing University, Nanjing 210093, China

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Metasurfaces are two-dimensional metamaterials with unprecedented capabilities for manipulating light through their ultrathin and flat architectures. Originally, metasurfaces employed subwavelength resonators to control the local phase of light. Later, their design was extended to non-resonant geometric (Pancharatnam-Berry) phases and dynamic propagation phases. The constituent materials of metasurfaces have extended from metals to all-dielectric to reduce the losses. Metasurfaces have provided numerous functionalities such as beam engineering, waveplates, polarizers, and holograms [1]. One popular application is metalens imaging, which promises extremely wide uses in optical systems [2]. Although the imaging performances of metalenses (e.g., efficiency, working bandwidth, field of view) have been improved by various methods, they are usually constrained by each other. Therefore, the comprehensive performance of today's metalenses is still inferior to the traditional refraction lenses and compound lenses.

Several good reviews have summarized recent progress on the design principles, performances, and applications of metasurfaces and metalenses [1,3]. The details will be omitted here. Instead, I discuss the application advantages of metalens technology, which is advancing rapidly. Metalenses offer two major advantages in imaging technology. First, their ultrathin, ultralight, and flat architectures favor minimization and compact devices. Second, their function multiplexing and expansion abilities provide extremely flexible wavefront shaping, polarization control, and spectrum tailoring. Unfortunately, in many previous works, metalenses were employed only as substitutes of traditional elements in complex optical systems, which still require additional components such as tube lenses, polarizers, and waveplates [1-3]. Therefore, the sizes and weights of whole imaging systems based on metalenses are seldom reduced, meaning that the core advantages of metalenses (ultra-lightweight and ultra-thin) are not exploited. Nevertheless, some exciting advances toward compact device applications have been made. Recent examples are metasurface spectrometry, eyepieces for augmented reality, and compact polarization cameras. Some compact devices have been inspired by living organisms such as jumping spiders and the compound eyes of insects. Although these devices do not reach the miniaturization level of insect organs, their developmental direction is becoming well clarified.

An important alternative design is the multi-level diffractive lens (MDL), which has demonstrated powerful capabilities as an achromatic flat lens [4]. The MDL design is based on conventional diffractive optics, but with optimized complex ring heights. Since the multi-leveled height of each ring can provide sufficiently tuned phases, the ring width can be much larger than the feature size of metalens, which greatly relaxes the manufacturing precision in the planar dimension. However, because the MDL has structural symmetry, it lacks the advantage of polarization control (which can be achieved by metalenses). We now briefly review the progress of achromatic flat lenses based on metalens and MDL. The constituent structure is becoming increasingly more complex, evolving from square nanoposts to rectan-

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*Corresponding author (email: taoli@nju.edu.cn) gular nanopillars and versatile hollow structures. These advances have been accompanied by improved achromatic bandwidth and efficiency performances. Intuitively, we can attribute these progresses to expansion of the parameter space of the structural design. Height has become the new dimension in MDLs, providing new opportunities for improving the MDL performance while lowering the requirements of the planar parameters. Thus, introducing more parameter spaces by further increasing the complexity is a possible route for furthering the imaging performance of metalenses and MDLs. Along this route, topological optimization assisted by advanced computation algorithms will play increasingly important roles in future work.

Future unique applications of metalenses (including MDLs) will likely draw on clues from past approaches. Despite great efforts in developing achromatic metalens, their applications remain very limited by the inevitable trade-offs of complex performances. For instance, the achromatic bandwidth must be delicately balanced against the lens size and numerical aperture (NA). A metalens with a moderate NA (e.g., 0.3) will be size-limited to ~100 μm, which greatly constrains its applications in high-quality imaging systems. I expect similar bottlenecks in the design trade-off and fabrication accuracy of MDLs. Other avenues of research have exploited the intrinsically large chromatism of metalenses. For example, a recent spectral tomography technique is based on the large chromatism of metalens and requires no phase compensation [5]. In principle, this technique is not limited by size or numerical aperture, and will provide high-resolution three-dimensional imaging. Especially, the achievement of compact and stable tomography devices without moving mechanical components is promising. From this viewpoint, appropriate application scenarios for metalenses are more important than merely improving a certain performance with other sacrifices in an unsuitable device.

In summary, the strongest advantages of metalenses are their miniaturization capability and function expansion potential. Although their imaging performances have remarkably improved, metalenses are ill prepared for massive replacement of the lenses in existing applications. Instead, new opportunities for metalenses have emerged in applications demanding compact integration, such as endoscopy, augmented reality, and compact bio-imaging. With their combined advantages of compactness and unique functionalities, metalens are expected to revolutionize optical technologies.

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