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Research Highlight

Achromatic metasurface lens at visible wavelengths

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Lenses, such as optical lens, electron lens, acoustic lens and so on, are devices that can focus waves to form an image. Since the invention of telescopes and objectives, optical lenses play important roles in observing objects from molecular to astronomical levels, and high-resolution lithography using optical, electron or X-ray beams. To improve the imaging quality, usually, the multiple lenses in a conventional system needs to be carefully designed and aligned to reduce the spherical aberration, coma, chromatic aberration, etc (see Fig. 1).

In optics, although diffractive optical devices, with subwavelength feature sizes, are also powerful for manipulating the wavefront of light, the fabrication of multiple phase steps is still very challenging. On the other side, the thickness or pixel size of spatial light modulators and MEMS are usually much larger than the wavelength of light, which inevitably limits the device miniaturizations. Fortunately, the advent of photonic metasurfaces [1–4], consisting of spatially variant *meta*-atoms of sub-wavelength pixel sizes, enables the new concepts and unprecedented abilities of controlling light. Among the various optical applications [1–5], metasurface lenses (metalens) [3,6,7] with high flexibilities of engineering the phase profiles of light and integrating multiple optical functionalities, have shown great potentials to complement or replace the conventional lenses. In one of metalens designs, spin-dependent Pancharatnam-Berry (P-B) [8,9] phase in optics provides an intuitive method to manipulate the phase of light by simply rotating the in-plane orientation angles of the birefringent *meta*-atoms. In this way, a metalens with full phase range from zero to 2π, can be fabricated in a single lithography process and its cost is much lower than that of conventional diffractive optical devices with the same number of phase steps [3,6]. The P-B type metalenses at visible and near-infrared wavelengths have been demonstrated by using plasmonic [3] and dielectric *meta*-atoms [6], respectively. In addition to P-B phase, the Huygens-type metasurface [10], consisting of high refractive index *meta*-atoms, represents an alternative to design various metalens devices.

Although the great progresses that have been made in the field of metalenses, the conventional techniques of reducing imaging aberration are still very useful. Fortunately, due to the fact that the metalenses have flat surfaces, in principle it is free of spherical aberrations. However, they usually suffer from comatic and chromatic dispersions. To solve the first issue, two groups designed doublet metalenses to reduce the comatic aberrations [11,12]. Last not least is how to correct the chromatic aberrations of metalenses, which finally limits the practical application of metalenses in full-colour imaging and microscopy. People have been thinking about the novel ideas to circumvent this constraint. Indeed, by using dielectric *meta*-resonators, achromatic metalens had been demonstrated for discrete wavelengths in the near infrared regime [13,14] and later in the visible but with very narrow bandwidth [15].

Facing all these difficulties in correcting the chromatic aberrations of metalenses, Wang and his collaborators from Nanjing University and Academia Sinica of Taiwan [16] proposed the idea of integrated-resonant unit elements (IRUEs), which takes the advantages of both the geometric P-B phases and phases of plasmonic resonant *meta*-atoms. They successfully corrected the chromatic aberration of a reflective metalens over a continuous wavelength range from 1,200 to 1,680 nm for circularly polarized light. While the NIR achromatic metalens based on IRUEs promises important applications in optical communications and near-infrared imaging and so on, it is however highly desirable if this method could be pushed to visible wavelength applications such as full-colour display and imaging.

Very recently, two fantastic works published in *Nature Nanotechnology* succeeded in demonstrating broadband achromatic metalenses at visible wavelengths by using dielectric metasurfaces [17,18]. In Ref. [17], Wang and his colleagues incorporated the P-B phase method with integrated-resonances (previously proposed in a plasmonic version [16]) for accomplishing the phase requirement over a continuous bandwidth. The integrated-resonance enables introducing various slopes in the phase spectrum (also regarded as different group delays [18]), which is the key characteristic for phase compensation in an achromatic metalens. Through using GaN-based *meta*-atoms, the fabricated achromatic metalens is capable of eliminating the chromatic effect spanning from 400 to 660 nm. The working bandwidth is about 49% of the central wavelength, to the best of knowledge, this is the state-of-the-art record in this field. Such design principle can be approached with other high index materials. For example, achromatic metalens working from 470 to 670 nm was realized by using TiO_2 [18]. In these two works, the authors employed both the P-B phase and phase from resonant *meta*-atoms coming from the waveguide modes of the dielectric (semiconductor) *meta*-atoms to meet the required

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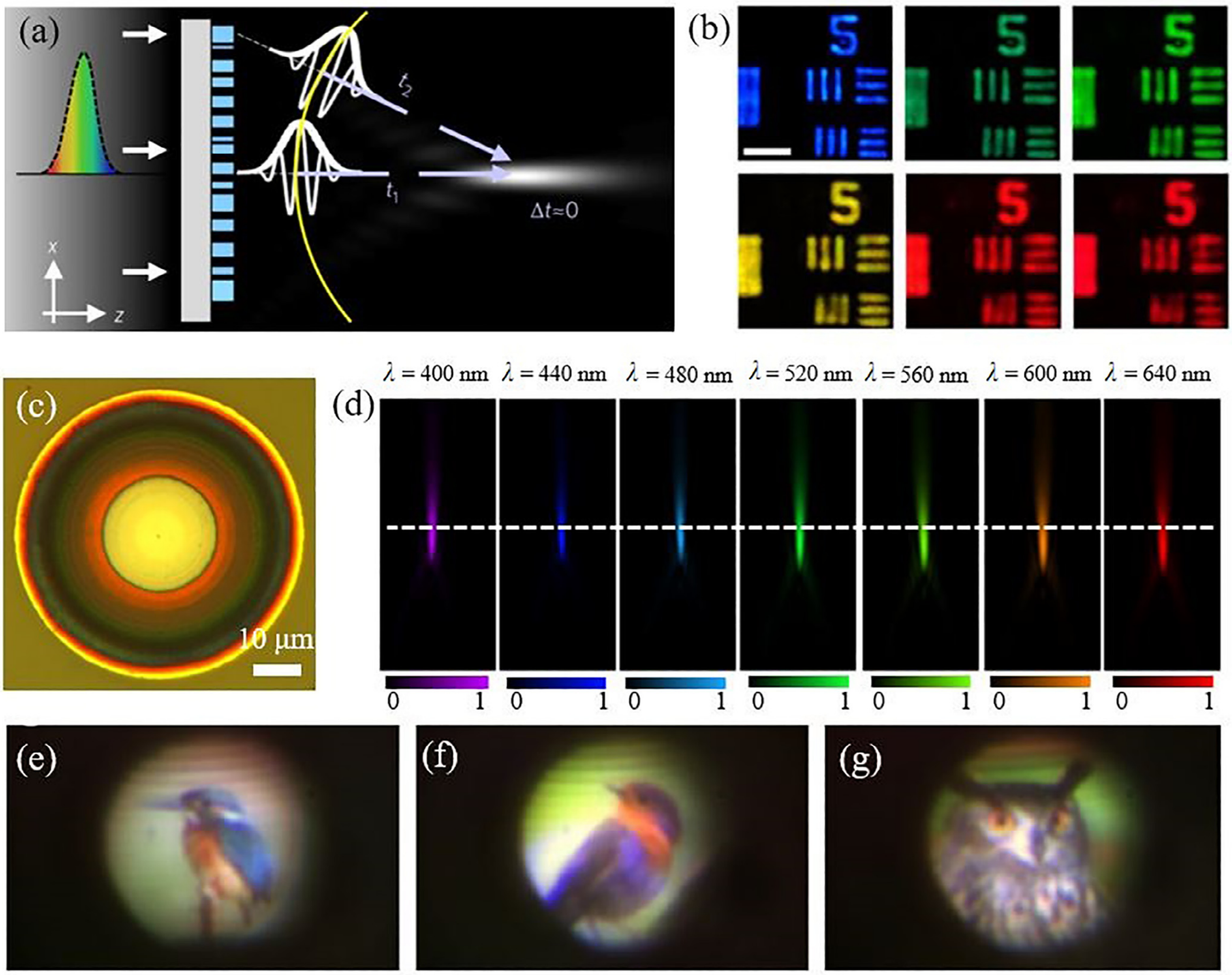

Fig. 1. (Color online) Broadband achromatic metalens in the visible. (a) Schematic of an achromatic metalens in Ref. [18], in which the phase profile satisfies specific conditions. The metalens is designed to exhibit spatially dependent group delays such that wavepackets with different wavelengths from different directions arrive simultaneously at the focus. (b) Images of 1951 United States Air Force resolution target formed by the achromatic metalens. (c) Optical image of the fabricated achromatic metalens in Ref. [17]. (d) Measured focusing performances for the achromatic metalens with NA = 0.106 at various incident wavelengths. The white dashed line indicates the focal planes. (e)–(g) Full-colour Alcedinidae, Erithacus rubecula and Eurasian eagle owl images captured by using the IRUE-type achromatic metalens. Adapted from Refs. [17] and [18].

phase profiles of an achromatic metalens. It is worthy to point out that the broadband achromatic metalenses for visible wavelengths is working in transmission mode, which is highly desirable for full-colour microscopic imaging and display.

In the future, much effort still needs to be dedicated to improvement of the achromatic metalens in terms of optical efficiency, size of the field of view and the cost of nano-fabrication and so on. However, given the present progresses, it is very promising that the achromatic metalenses will bring more applications in the visible, infrared, Terahertz and microwave regimes, etc.

Conflict of interest

The authors declare that they have no conflict of interest.

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