NANOPHOTONICS

Imaging the rainbow

Dielectric metalenses made of high-index materials can compensate material dispersion to achieve broadband imaging in the visible.

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Traditional optical lenses focus light by altering its wavefront through the addition of a spatially dependent phase to the light field as it propagates through a dispersive medium. With the desire to integrate optical and electronic components for applications such as wearable optics or optical communications, the demand for compact, lightweight, yet high-performance optical systems is steadily increasing. Towards this goal, in the past few years, researchers have reported various approaches to realize ultrathin optical elements based on nanostructured surfaces (metalenses), demonstrating the potential for altering the light propagation in an efficient and convenient way[1,2]. However, these designs suffer from strong chromatic aberration, making them unsuitable for precise imaging of objects with multiple colours. Writing in *Nature Nanotechnology*, two groups now report metalens designs that allow achromatic imaging in the visible range[3,4]. Both groups use nanofin structures made of high-index dielectrics to add a spatially dependent phase to the light field.

As illustrated in Fig. 1a, a common refractive lens made of a regular optical glass focuses white light to different focus spots, corresponding to the different colours, along the propagation axis; thus resulting in a blurred focus spot (the chromatic aberration). The origin of this behaviour is the dispersion of the material's refractive index with respect to the light wavelength, which is inherent to all materials. In conventional imaging systems, chromatic aberration can be reduced by using two lenses — one with a positive and the other with a negative dispersion property (Fig. 1b). These 'achromatic' lenses improve the image quality when using a broadband illumination, as the image will reconstruct for a wide range of colours at the same plane. Unfortunately, as demonstrated in Fig. 1, this adds even more optical components to the imaging system, making it heavier, larger and more expensive — clearly not an option for miniaturized optics.

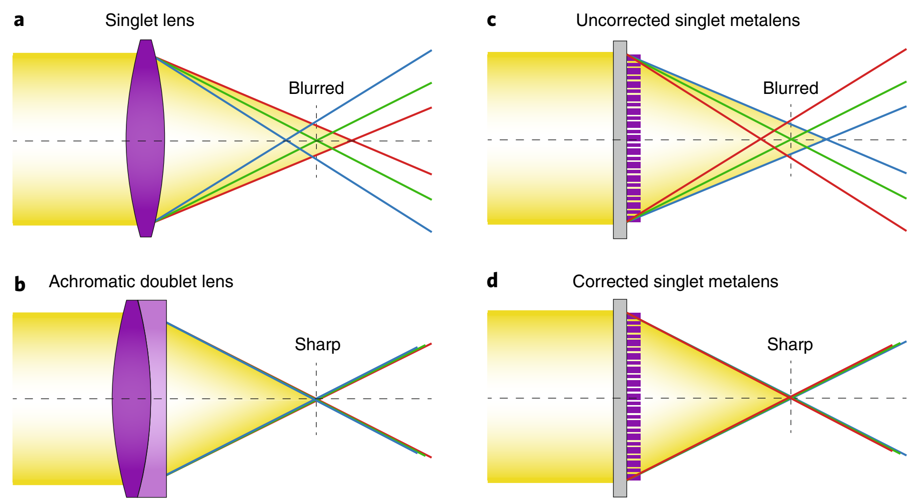

Fig. 1 | Focusing of white light with lenses. a, The dispersion of a regular singlet lens made of optical glass leads to different focal distances for different wavelengths. **b**, Two different lenses made of different materials (like crown and flint glasses) forming a doublet lens can compensate the chromatic aberrations. **c**, Regular metalenses resemble a singlet lens and show chromatic aberrations. **d**, Chromatic aberrations can now be compensated solely by design without the need for additional materials or lenses[3,4].

Metalenses can potentially break this cycle of adding more optical components to improve the imaging quality while having the potential of being easily integrated into optical systems. It has been shown, for example, that they can image objects at single wavelengths and control beam shapes[5,6]. Furthermore, they can be used for holographic applications and nonlinear optics. However, to generate high-quality colour images, they need to work over the entire visible wavelength range. Up to now, metalenses have suffered from strong chromatic aberrations in the same way as conventional lenses do, that is, the focal length varies with the wavelength (Fig. 1c), only the sign of the aberrations is opposite due to the diffractive working principle, resulting in a shorter focal length for longer wavelengths.

In their reports, Chen et al. and Wang et al. show how to compensate for the chromatic aberration of dielectric metalenses. Chen et al. utilized a meta-atom design consisting of two TiO_2 nanofins spaced close to each other[3] (Fig. 2a). The close proximity of the nanofins results in the formation of optical modes similar to modes found in slot waveguides. The researchers found that such modes can be used to add an additional phase to the wave by adjusting the size of the two fins. As a result, the effective optical mode possesses different fractions in either the high-index fins or the low-index air gap. Based on this added degree of freedom in the design, the researchers were able to independently control the phase and group delay over nearly the entire visible spectral range, and compensate for the chromatic dispersion effect of the lens.

Wang et al. followed a slightly different approach in that they used single GaN nanofins as meta-atoms[4] (and inverted versions) that support higher-order resonant modes in each nanofin, in analogy to cavity modes in resonators (Fig. 2b). As these modes depend strongly on the wavelength, the researchers were able to demonstrate that these 'resonator modes' can be used to add a wavelength-dependent phase to compensate for the diffractive dispersion effect of the metalens.

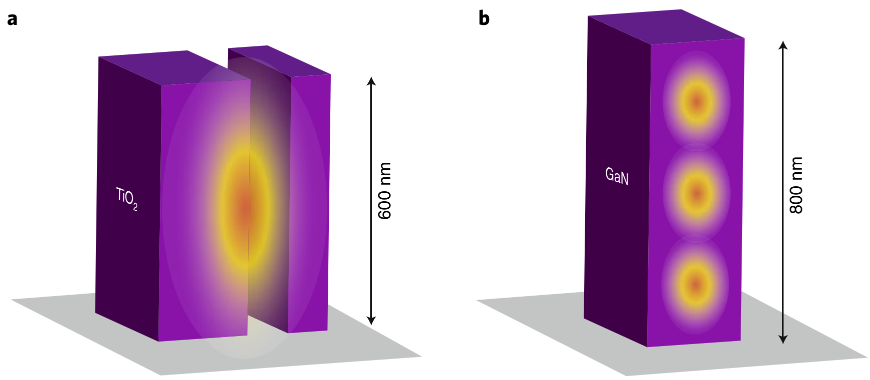

Fig. 2 | Schematics of the meta-atom unit cell for the two design approaches. a, Meta-atom design by Chen et al. based on two TiO_2 nanofins in close proximity[3]. An effective optical mode is passing through the structure, whereas the gap between the fins alters the dispersion properties of the light. **b**, Alternative design by Wang et al. using a single GaN nanofin with larger height as a resonator[4]. The high index of GaN leads to the formation of optical modes similar to standing waves found in Fabry–Pérot resonators. By altering the width and length of the nanofin, the dispersion of these modes can be changed while keeping the phase accumulation of the light the same.

As a result, both groups achieved a singlet achromatic metalens suitable for imaging applications in the full visible range (Fig. 1d). The concepts used by both groups demonstrate the high flexibility in designing optical elements with nearly arbitrary spatial phase profiles and dispersion properties without the need for additional optical elements or materials. This is a great advantage as the size and the fabrication cost of their achromatic metalens is likely to be the same cost as an uncorrected metalens. It is important to note, however, that the added degree of freedom in the design of the group delay dispersion significantly lowered the focusing efficiency of the device from over 90% to below 50% compared to previously uncorrected metalenses. Such reduction in efficiency results in lower image brightness and reduced contrast due to unwanted background noise. Furthermore, the performance of the metalenses strongly depends on the polarization state of the light. This largely limits their use for a wide range of imaging applications, as it would require additional polarization optics. Further optimization is therefore still needed before we can think of using metalenses in everyday-life devices. ❐

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