https://doi.org/10.1038/s41566-023-01306-w

Inconsistencies of metalens performance and comparison with conventional diffractive optics

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We posit that inconsistent interpretations of experimental data have led to inaccurate claims on metalens focusing efficiencies. By performing a meta-analysis, we show that extraordinary claims of high focusing efficiency at high numerical apertures are, unfortunately, not yet backed by rigorous simulation or experimental results.

Fresnel-zone plates, as well as their generalizations via multilevel and effective-medium implementations, including those containing subwavelength features, have been traditionally considered under the umbrella of diffractive lenses[1]. Recently, flat lenses containing subwavelength features have been termed metalenses[2]. This definition encompasses phase Fresnel-zone plates with numerical aperture (NA) >0.5, as well as related devices such as photon sieves, superoscillating flat lenses, super-lenses, transformation-optics-based lenses, radially polarized focusing lenses, photonics-crystal-based lenses and others. It is noted that effective-medium theory was used to map desired phase transformation into subwavelength features before the introduction of the term metalens[3]. The term is quite comprehensive, making it somewhat unnecessary to differentiate it from diffractive lenses. However, proponents of metalenses claim two advantages: higher focusing efficiencies at high NA and multi-functionality, suggesting that diffractive lenses lack these attributes[2,4]. Unfortunately, we find that there is no clear evidence to justify either of these claims. This Comment urges the scientific community to conduct systematic research to substantiate these benefits.

The focusing efficiency of diffractive lenses decreases at high NA[5]. But, this decrease can be avoided by local-geometry optimization[6], without resorting to any new physics.

An analysis of the published literature on metalenses shows that many reports of metalens-focusing efficiencies might be inaccurate or inconsistent. The focusing efficiency, η, is the fraction of incident power that is focused. The focal power is typically measured with an iris, the radius of which ranges from 3× to ≥18× the full-width at half-maximum (FWHM) of the focal spot, and sometimes with no iris at all[7]. If all incident light is diffracted into one converging spherical wave and when NA $\lessapprox$ 0.8, then the iris radius is not important as long as it is greater than about 3× FWHM (see the ideal Airy disk in Fig. 1a). However, a real flat lens diffracts light into multiple orders (Fig. 1b). Then, a large

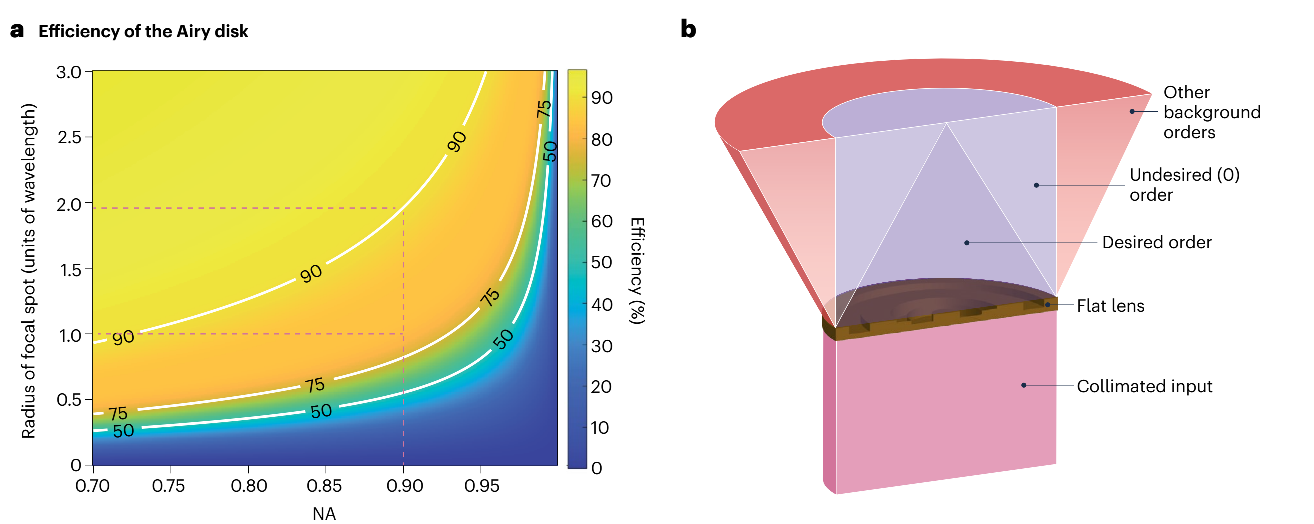

Fig. 1 | Focusing efficiency of the ideal Airy disk and illustration of diffraction orders from flat lenses. **a**, Focusing efficiency, η, of the ideal Airy disk as function of NA and the radius of the focal spot, R (normalized to FWHM = 0.5λ/NA, where λ is wavelength). For NA $\lessapprox$ 0.8, η is stable for R > 3× FWHM. But for higher NA, η varies rapidly with R. **b**, All real flat lenses generate not only the desired diffraction order but also a multitude of undesired orders. Therefore, if $R \gg$ FWHM, then the focusing efficiency can be grossly over-estimated.

iris radius grossly over-estimates focusing efficiency. For example, refs. 8,9 use irises of radius 8.5× and 40× FWHM, respectively, whereas ref. 7 does not use an iris. In some cases, focusing efficiencies higher than those theoretically possible (bounded by a unit-cell-based design)[10] have been reported (Supplementary Table 1). The unit-cell-based design is not capable of precisely representing the necessary phase transformation, which results in undesired diffraction orders. This problem was thoroughly analysed several decades ago[11], and more recently revisited[12]. To build upon ref. 12, here we have quantitatively analysed the details from numerous papers and clarified where these claims might be invalid (Supplementary Information). Although there are discrepancies in the proposed characterization methods in ref. 12 (Supplementary Information), we agree with the key message that it is important to establish a direct comparison between the focusing efficiency (and performance, in general) of a metalens and that of an optimized diffractive lens (similar to the ones described in ref. 6) with the same specifications.

There might also be inaccuracies in the calculations of the Strehl ratio (SR) and the modulation-transfer function (MTF). To obtain SR, the measured PSF is normalized to the Airy function by matching their encircled powers (area under the curve of the PSF). For example, in ref. 13, this normalization is performed by integrating the power over a radius of only 3× FWHM. The MTF is often calculated as the absolute value of the Fourier transform of the PSF. However, the PSF is often prematurely truncated (often due to the limited field of view of a magnifying objective). This causes both the SR and MTF to be over-estimated.

The second advantage of multi-functionality is claimed based on the observation that a metalens "can function differently depending on different degrees of freedom of light (wavelength, polarization, incident angle and so on)"[4]. We note that 'conventional' diffractive optics have long performed different functions based on polarization[14], wavelength[15] and incident angle[16].

By dramatically increasing the number of degrees of freedom, subwavelength diffractive optics offer a treasure trove of possibilities for imaging and inferencing. However, there is a clear need to establish these advantages with rigorous experiments to advance their adoption.

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Published online: 31 October 2023

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Acknowledgements

Support from grants N6560-NV-ONR and NASA NNL16AA05C are gratefully acknowledged. We thank H. Smith, H. Li and O. Miller for fruitful discussions.

Competing interests

R.M. has financial interest in Oblate Optics, Inc., which is commercializing flat lenses.

Additional information

Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s41566-023-01306-w.

Peer review information *Nature Photonics* thanks Uriel Levy and the other, anonymous, reviewer(s) for their contribution to the peer review of this work.