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Large-area, high-numerical-aperture multi-level diffractive lens via inverse design: comment

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The memorandum [Optica 7, 252 (2020).; Optica 7, 1323 (2020).] is devoted to the design, fabrication, and characterization of an optimized multi-level diffractive lens, emphasizing the advantages of the multi-level approach compared to the metalens approach. While such advantages may well exist, we feel that a number of statements in the memorandum require clarification. We add some references on multi-level diffractive lens optimization that place the memorandum's contributions in a more complete context. © 2021 Optical Society of America under the terms of the OSA Open Access Publishing Agreement

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We comment on a recent *Optica* memorandum [1,2].

In the 90s, photonic research was starting to enjoy the benefits of nanotechnologies, and about 10 groups in the world were working on the use of nanostructures for beam shaping and imaging. Initial designs were guided by effective medium theory, based on the idea that progressively varying and sufficiently small binary features would mimic an index gradient and thereby achieve beam shaping or beam steering [3,4]. Following early work at larger wavelengths [3,5,6], some of the first devices for visible light operation were obtained by etching fused silica with advanced nanofabrication facilities [7,8]. However, for some time, it remained a challenge for these early components to reach diffraction efficiencies similar to those of lower cost sawtooth-profile counterparts.

At that time, in fact, for any design and technology, large deviations together with high efficiencies were considered extremely challenging [9,10]. It was then realized that effective medium theory approaches suffered the same limitation as sawtooth profiles, namely a zone edge shadow effect that spills away an increasing fraction of the incoming light as the spatial frequency increases. Designing subwavelength beam shaping components as arrays of high-index single mode nanowaveguides was identified as a possible cure [11]. This paradigm shift allowed the fabrication and characterization of metaprisms etched in TiO_2 films on glass for operation at 633 nm, as evidenced by the remarkably large efficiencies for large deviation angles [11]. Similarly, a metalens with half of its surface covered with zone widths smaller than 3λ showed an efficiency of 80% (absolute value not compensated for Fresnel reflection losses) [11]. The new perspectives offered by the so-called blazed binary (to emphasize that, albeit binary, they are efficient) components for imaging were summarized in Ref. [12].

The blazed binary components fabricated some 20 years ago are essentially identical in their conception (same waveguiding effect) and realization (same materials) to those presently studied under the names of metalenses, metaprisms, as strikingly evidenced by Table 1 in Ref. [13], which retraces the history of ideas on focusing with metasurfaces (see also the record of a recent seminar [14]).

This introduction places two references of the memorandum into proper context, the 1999 JOSAA article [11] (Ref. [6] in Ref. [1]) and the expert-opinion article [13] (Ref. [15] in Ref. [1]).

Regarding the second paragraph in the memorandum of Ref. [1], earlier works by the memorandum authors are compared with blazed binary diffractive lenses, with the claim that the latter "suffer from relatively low efficiencies." It is stated that some of the memorandum authors recently showed "that high efficiency at all NAs could be achieved."

First, it is inappropriate to distinguish early work on blazed binary elements from more recent work on metasurfaces. The design, analysis, and fabrication technologies are the same. Only the sophistication of the tools has changed. Second, by offering Refs. [4,5] in Ref. [1] as the only representatives of the field of metasurfaces in the 90s, the remarkable experimental results reported at that time are ignored (see for example Refs. [13,14,16–20] in Ref. [13]. The series of articles indicates diffraction efficiencies on the same order as that reported by some of the memorandum authors in Ref. [8] of Ref. [1]; furthermore, the 80% absolute efficiencies in Ref. [10] are experimental values obtained for gratings and lenses, whereas Ref. [8] in Ref. [1] provides theoretical values only.

One may also wonder why a 1 cm, 0.9 NA metalens (Ref. [2] in Ref. [1]) is called small.

Regarding the paragraph following Fig. 2 in the memorandum of Ref. [1], by inappropriately pointing at errors and inconsistencies

in earlier reports on metalens experimental characterization, the memorandum insinuates either poor science or nefarious intent. However, a careful reading of the literature offers a simple technical explanation, namely monochromatic versus polychromatic operation.

The memorandum authors describe as "particularly troubling" a recent science report (Ref. [18] in Ref. [1]) on large NA metalenses "because the claimed focusing efficiency of 86% at NA = 0.9 has been repeated in various reviews" [15]. They state further that the 86% efficiency "is far higher than what is theoretically predicted to be possible in a recent article" which mentions an "upper bound on efficiency for a NA = 0.9 metalens of 32%," further suggesting that the literature on metalenses contains many "pitfalls" (next sentence).

An experimental efficiency $\approx 3\times$ larger than a theoretical upper bound obviously calls for further look into the seemingly paradoxical observation; in fact, the upper bounds of Fig. 7(b) in Ref. [15] (Ref. [3] in Ref. [1]) are derived for a broadband (450–700 nm) operation of a broadband optimized component, whereas the 86% efficiency (like the efficiencies in Ref. [1]) concerns monochromatic operation of a component optimized at that wavelength. Comparing broadband and monochromatic operations to try to discredit a work is surprisingly inappropriate.

Finally, let us stress that the lens reported in Ref. [11] by the present authors has been characterized carefully; not only has the efficiency been measured, but quantitative data are given about the geometrical aberration. In the memorandum, no such figures of merit are given. It is just said that there are no sidelobes in the PSF, which in fact means that the outer zones are not highly efficient (apodization). Also, Ref. [1] lacks indication on the scale of the U.S. Air Force chart on how the measured MTF/PSF data have, as is claimed in the last column, been compared with theory (no simulation result is given), and also appears to ignore the fact that a 0.9 NA lens, even with a 4.13 mm diameter, cannot have the same spherical aberration and, therefore, the same MTF/PSF, under collimated illumination and at $\times 2$ magnification {Fig. 2(d) in Ref. [1]}; indeed, if the component is assumed to be optimized for collimated illumination, the spherical aberration at magnification $\times 2$ is on the order of several hundred wavelengths. That suggests that the imaging test with the Air Force resolution chart has been recorded under illumination conditions that did not cover the full MLD lens aperture.

Commenting Fig. 2(c), we read the following in Ref. [1]: "instead of a single efficiency number, we prefer to plot the experimental relative encircled power as a function of the radius from the center of the focused spot in Fig. 2(c). The relative encircled power is defined as the ratio of the optical power within a spot centered on the optical axis of a given radius to the total incident power. Here, we approximate the incident power as the total power in the frame used to capture the PSF." We acknowledge that the encircled power is a common metric used to characterize refractive lenses. However, it is used as a measure of resolution, not efficiency. It appears from Fig. 2(c) that the frame used in Ref. [1] to capture the PSF was a disk of radius approximately 13 FWHM, which is fairly small. It is, thus, not surprising that 90% of that light reaches a disk of radius 10 FWHM. However, a significant fraction of light directed to spurious orders may be missed out. The slope discontinuity on Fig. 2(c) when the encircled energy curve hits 100% is a hint that such a bias may exist.

Regarding previous work on "inverse design" of multi-level diffractive microlens optimization, we agree with the memorandum that high-performance diffractive lenses can be achieved by optimizing the transition point locations of multi-level zone plates. But previous works on diffractive lens optimization should be mentioned in that context (see for example the impressive optimized efficiencies achieved in Ref. [16–19] or the experimental evidences in Ref. [12,19]).

The abstract in Ref. [1] further emphasizes that optimized multi-level diffractive lenses may offer lower fabrication costs compared to metasurfaces, as they could be cost-effectively replicated in polymers. That might be true, but it remains to be demonstrated.

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Large-area, high-numerical-aperture multi-level diffractive lens via inverse design: reply

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We proposed the use of relative encircled power as a measure of focusing efficiency [Optica 7, 252 (2020)]. The comment [Optica 8, 1009 (2021)] has raised useful questions, which we address briefly here and provide some clarifications. © 2021 Optical Society of America under the terms of the OSA Open Access Publishing Agreement

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In the pioneering work of Ref. [1], the authors demonstrated an impressive 80% diffraction efficiency. With no intention of minimizing this achievement, we first note that diffraction efficiency and focusing efficiency are not the same, and focusing efficiency was unfortunately not reported in Ref. [1]. When a diffractive element (including a lens) is illuminated by a plane wave, the transmitted light may be decomposed into basis functions. In the case of lenses, these basis functions are usually spherical waves, where the diffraction orders represent the center of these spheres (positive and negative signs refer to converging and diverging spherical waves, respectively) [2]. The diffraction efficiency is the ratio of power carried by one of these spherical waves to the total incident power. When a lens is illuminated normally by a plane wave, the intensity in the focal plane can be written as the sum of contributions from the different diffraction orders, $I(\rho) = I_0 + I_{+1}(\rho) + I_{-1}(\rho) + \ldots$, where the subscript denotes the order of diffraction, and ρ is the radial coordinate in the focal plane. Let us take the example of a perfect lens, where the diffraction efficiency is 100% (into the +1 order), $I(\rho) = I_{+1}(\rho)$ and from Fourier optics, we know that this is the Airy function, $I_{A0}\left(\frac{2J_1(x)}{x}\right)^2$, where, I_{A0} is the incident intensity, $J_1(x)$ is the Bessel function of the first kind, and $x = \frac{\pi\rho}{\lambda f\#}$, where λ is the wavelength and $f\#$ is the f-number of the lens. Focusing efficiency was first introduced as the fraction of incident power within a focal spot of radius equal to 3 times its full width at half-maximum (FWHM) [3]. We can generalize this by calculating the power within a spot of a general radius, R as

$$E_A(R) = \int_0^R I_A(\rho)\rho \mathrm{d}\rho = E_{A0}\left(1 - J_0^2\left(\frac{\pi R}{\lambda f\#}\right) - J_1^2\left(\frac{\pi R}{\lambda f\#}\right)\right), \tag{1}$$

where E_{A0} is the total incident power. Finally, the focusing efficiency is simply given by (this is also called the relative encircled power),

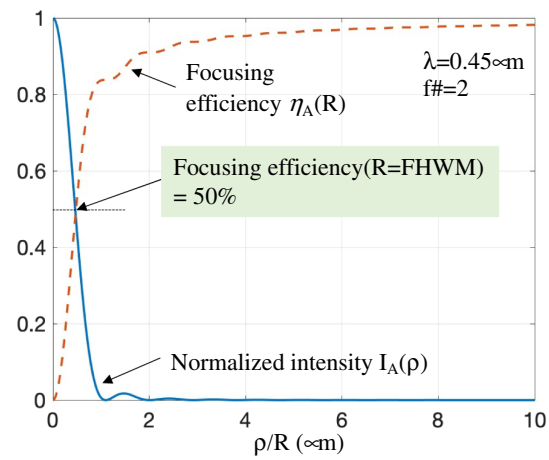

Fig. 1. PSF and encircled power of a lens with 100% diffraction efficiency achieves a focusing efficiency of 50% for a spot-radius equal to FWHM. It is important to report the spot-radius along with focusing efficiency.

$$\eta_A(R) = \frac{E_A(R)}{E_{A0}} = \left(1 - J_0^2\left(\frac{\pi R}{\lambda f\#}\right) - J_1^2\left(\frac{\pi R}{\lambda f\#}\right)\right). \tag{2}$$

The subscript A refers to the ideal lens, whose point spread function (PSF) is the Airy function. From this expression, we can readily show that the focusing efficiency when $R = \mathrm{FWHM}$ of the PSF is 50% (Fig. 1). **In other words, a lens with 100% diffraction efficiency has focusing efficiency of 50% (measured with R = FWHM).** The focusing efficiency will be $>\sim 90\%$, if $R = 3 \times \mathrm{FWHM}$. This example illustrates that reporting focusing efficiency without the value of R is not sufficient to give the full picture.

The commentors take issue with our critique regarding Ref. [4]. The gist of our comment was that the focusing efficiencies reported in Ref. [4] are higher than what is theoretically predicted possible

with the concept of unit-cell design, as clearly explained in Ref. [5], both for monochromatic and broadband cases. This is a good example of a confusion arising from inconsistency in the size of the focal spot. Since the size of the focused spot used to compute focusing efficiency was not explicitly reported in Ref. [4], it is as well possible that the focusing efficiency reported there used a different focal spot than what was used in Ref. [5] for calculation of the upper bounds of focusing efficiency (where radius corresponding to the first zero in the PSF was used). This example simply proves our point in Ref. [6] that relative encircled power is a better metric for a lens than just a single value of focusing efficiency. In fact, we would like to correct the comment that relative encircled power is only a measure of resolution, which is clearly not correct, as can be seen by the example of the Airy PSF above. In fact, the relative encircled power is a measure of both resolution and efficiency.

Next, we acknowledge the criticism from the commentors that the relative encircled power in Ref. [6] was overestimated because the total incident power was underestimated due to the limited frame size of our recorded image. We also note that this same mistake is likely present in the vast majority of the flat-lens publications, including the ones cited by the commentors in their review paper. For example, one can examine Fig. 4 of Ref. [3] or Fig. S1 of Ref. [7] to note that the total incident power is underestimated due to the limited field of view of the microscope objectives used in both cases, which in turn leads to an overestimation of the measured focusing efficiencies.

The commentors stated, referring to our work that "*1-cm, 0.9-NA metalens* (Ref. 2 in [6]) *is called small.*" There are three reasons why we chose to ignore the metalens referred here. First, we note that this lens has $\mathrm{NA} = 0.78$ and not 0.9. Second, this metalens is a negative lens. Third, no experimental validation of the PSF or modulation transfer function (MTF) of this lens was provided that could validate the reported NA.

Finally, the commentors brought up an observation about a lack of scale in Fig. 2(d). We apologize for this oversight, as we naïvely assumed that the standard Air Force chart image is well known. Our results showed that the lines in Group 7, Element 6 (size $\sim 2\ \mu\mathrm{m}$) were resolved, which is consistent with the reported PSF and MTF data.

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