# Reducing weight of imaging systems with flat lenses

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**Abstract:** The weight of many imaging systems are dominated by optics, especially at large apertures. Flat lenses can mitigate this problem by: (1) The weight of one flat lens can be many orders of magnitude lower than that of a corresponding refractive lens; (2) A flat lens can perform the function of multiple conventional lenses, thereby reducing the number of components; and (3) The flat lens can enable new capabilities that are not accessible with conventional lenses as summarized below.

**Introduction:**
In conventional optics, an ideal lens is one that imparts a *parabolic phase* on an incident wavefront of light, thereby converting an incident plane wave into a converging spherical wave. Such a strict phase requirement dictates that a single lens surface is unable to correct for image aberrations, including chromatic aberrations. Practically speaking, this means that most imaging systems require more than a single lens-surface. This leads to (1) thicker and (2) heavier cameras, (3) complexity in manufacturing due to requirement for precision alignment between multiple lenses, and (4) compromise in imaging performance (eg. operating bandwidth).

However, we discovered that this requirement of parabolic phase is not a strict constraint. In other words, we discovered a large number of phase functions that can all perform equally as a close-to-ideal lens. This means that one can now apply various numerical methods to choose lens-phase distributions that are optimal for desirable properties such as achromaticity, minimize off-axis aberrations, manufacturability, etc. Since the lens is a ubiquitous component in all imaging systems, such a relaxation of design space has enormous implications for creating: (1) ultra-thin and (2) ultra-lightweight cameras, (3) drastically simpler assembly (due to the absence of precise alignments) and (4) almost no compromise in performance (eg. very large operating bandwidths).

Our flat multi-level diffractive lenses (MDLs) are comprised of unit cells (or pixels), whose size is optimized to enable aberrations-minimized imaging. A photograph of an example MDL is shown in Fig. 1a. Since these pixels may be defined either as square pixels (Fig. 1b) or as concentric rings (Fig. 1c), this enables free-form optics or radial symmetry, respectively. A good overview of MDLs and comparison to alternative thin optics technologies is available in ref [4].

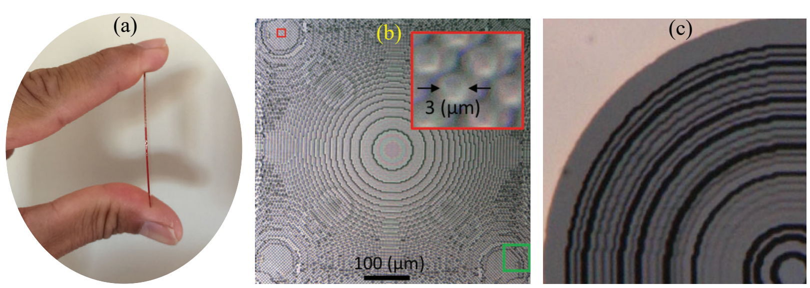


Fig. 1: Overview of MDLs. (a) Photograph showing an MDL fabricated in a 2.3μm-thick polymer film atop a 0.6μm-thick glass wafer. Optical micrographs of a portion of (b) a free-form MDL and (c) a radially-symmetric MDL.

The MDLs are designed via nonlinear optimization methods (such as gradient-descent assisted direct-binary search) that enables the choice of the MDL microstructure so as to minimize image (including chromatic) aberrations, while maintaining high focusing efficiencies. Our methodology also enables the direct application of fabrication tolerances, resulting in robust designs. Details of the design methodology have been described in these references. The MDLs can be manufactured via imprint lithography at low cost and at high volumes. The major steps are the fabrication of a master pattern and then the replication into daughter (final) patterns. The master pattern may be fabricated via multiple lithography and etch steps  or via grayscale lithography. The replication may be achieved in wafer-to-wafer, die-to-die or roll-to-roll processes. In each case, the imprinted polymer may be UV or thermal cured. The specific manufacturing process will be determined by the fabrication tolerance requirements of any given design. Oblate Optics has the capability to implement any of these required processes depending upon the design requirements.

Although diffractive flat lenses have been used in imaging before, they have poor performance due to aberrations (chromatic and off-axis). We have combined new theoretical insights, nonlinear optimization based design, and high-resolution grayscale nanofabrication to demonstrate flat Multi-level Diffractive Lenses (MDLs) with high numerical aperture (NA > 1.3 under water immersion) (low f/#) [1,2] and covering the visible,[3-5] near infra-red,[6] short wave-infrared,[7] longwave infrared [8], ultra-violet [9] and the Terahertz bands.[10] We have also combined two MDLs to create telescopes with varying magnification. [11]

MDLs have been experimentally demonstrated in all relevant spectral bands: visible, near-IR, SWIR, MWIR, LWIR and THz. More recently, we have even demonstrated a single MDL that is achromatic from the visible to the LWIR. Recently, we have also shown that the MDLs can be designed for significantly larger depth-of-focus, which can remove the need for focusing mechanisms, potentially reducing SWAP even further.

The weight of an MDL is dominated by its support substrate. By keeping this substrate very thin, one can achieve orders of magnitude reduction over the weight of the refractive counterpart. The MDLs can be fabricated directly into dielectric materials like glass, Silicon, but also could be patterned in transparent polymers. Since the device thickness of the MDL can be small (~ 2λ), then even absorptive polymer films could be used with good performance. Scalability to large apertures is feasible by either segmented MDLs or by patterning large areas via imprint lithography or combinations of the two.

**Experimennts:**

As mentioned earlier, the MDL can be used to perform the function of multiple conventional lenses. This concept can be illustrated by a single MDL that is achromatic over a large bandwidth, such as the visible band [3-5]. But we can a step further, and show that MDLs can achieve achromaticity over bandwidths that are several orders of magnitude larger than what is possible with conventional lens systems. For example, we showed that a single MDL can be achieve achromatic imaging (and focusing) from the visible (450nm) to the LWIR (15mm) without changing its focal length.[12] A second example can be seen in an MDL, whose depth of focus was increased by several orders of magnitude over that of a conventional lens. [13] Compared to metalenses, MDLs have the advantages of easier manufacturing and thereby, easier scaling to larger areas. [14]

We designed, fabricated and characterized a 100mm-diameter visible-band MDL as illustrated in Fig. 2. The device had a focal length of 200mm and operating bandwidth from 400nm to 800nm. We illuminated the MDL with a white-LED flashlight, placed far enough away to ensure collimated illumination and recorded the focal spot as indicated on the right. The spot-size was approximately 2μm.

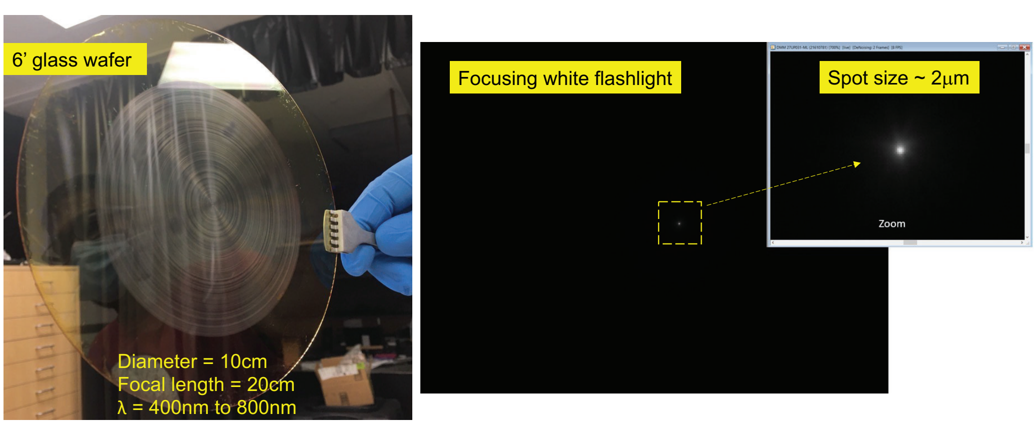

Fig. 2: Left: photograph of fabricated 100mm-diameter f/2 MDL. Right images: Focused spot with white light.

**Potential Impact of surface roughness:**

In our preliminary experiments, the MDL was fabricated in photoresist using grayscale lithography. Since this method leaves partially developed photoresist, it is important to understand the impact of the resulting surface roughness on the lens performance. We performed a careful simulation study to analyze this.

First, we measured the fabricated ring heights as well as surface roughness parameters for two copies of the same MDL design (see Fig. 3). The measured ring heights were compared to the designed values and an average error between 225nm and 313nm were estimated for the two MDLs. The corresponding standard deviations were 123nm and 174nm, respectively. Note that the average error has minimal impact on performance (as it is approximately a dc offset), but the standard deviation is more critical.

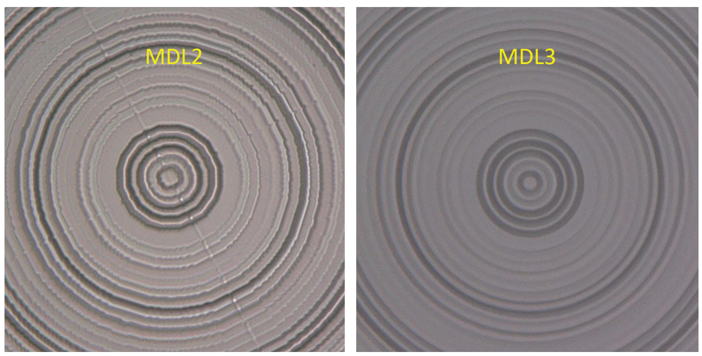


Fig. 3: Optical micrographs of the center portions of two identical MDLs used to perform metrology and surface roughness measurements.

The measured data is summarized in Fig. 4.

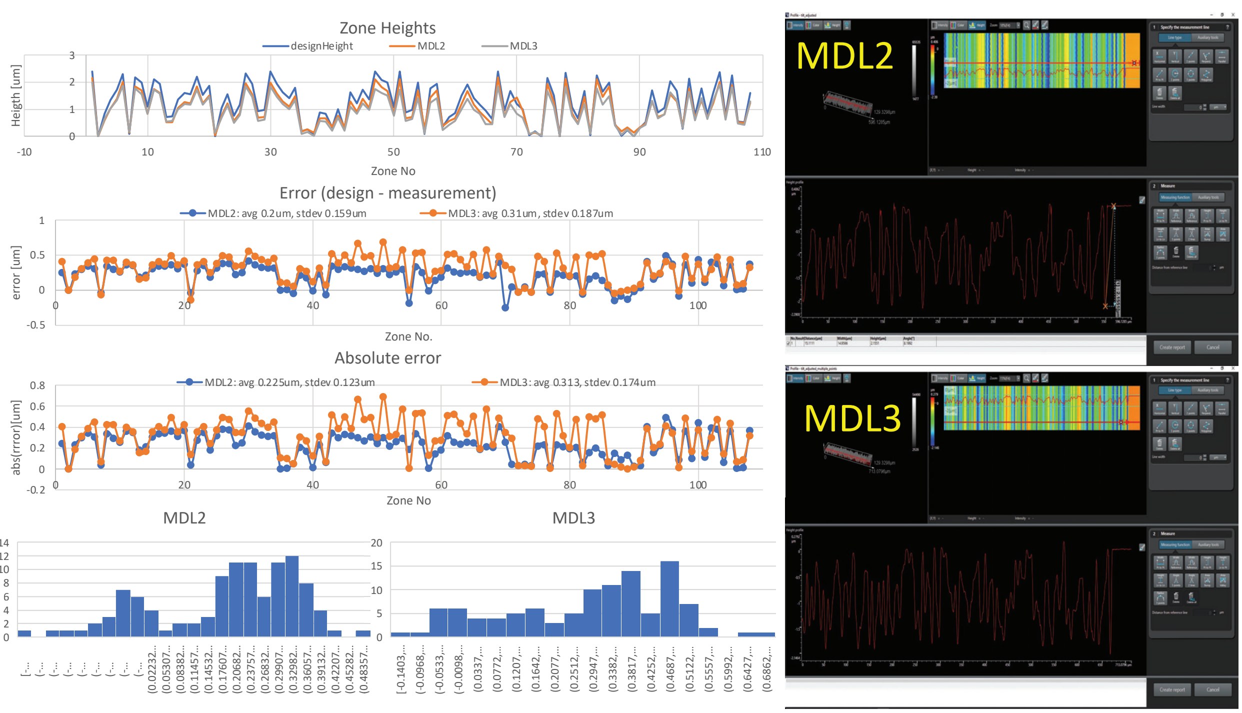


Fig. 4: Metrology results of the MDLs shown in Fig. 3.

The surface roughness of the device was measured by scanning an area of 400x400µm and measuring roughness along 5 horizontal lines (1-5) and 5 vertical lines (6-10) as shown in Fig. 5. The amplitude was 0.0299µm (avg) and period = 2.516µm (avg).

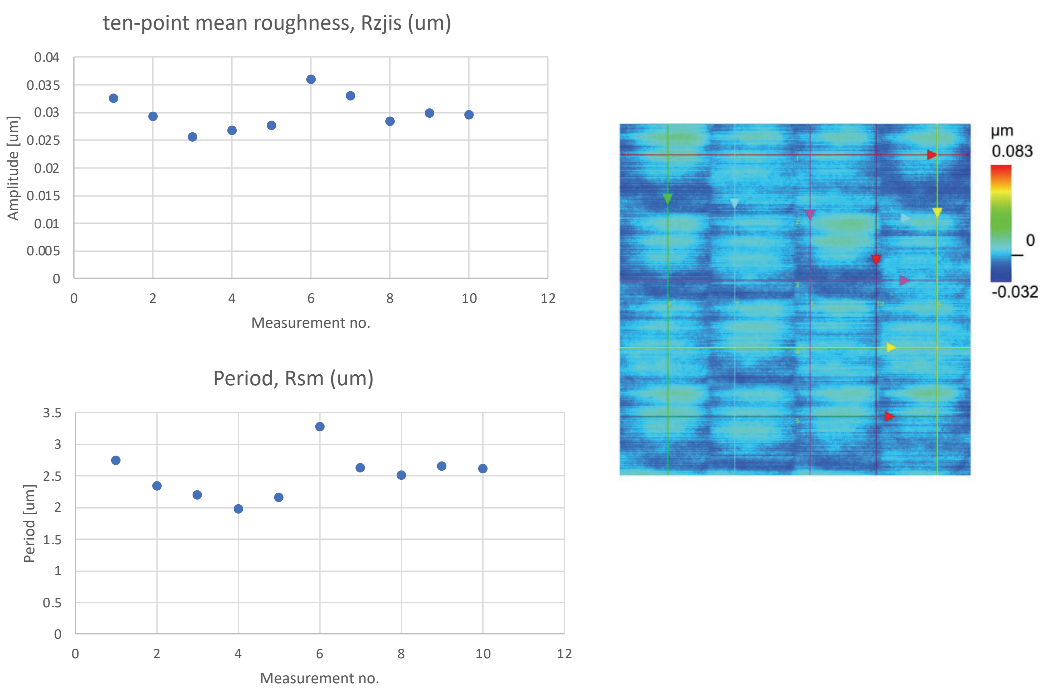


Fig. 5: Surface roughness measurements.

Finally, the surface roughness was modelled using a rectangular sinusoid on the MDL profile and PSFs were simulated under different roughness conditions. A small example MDL was used for the simulations to speed up the analysis as illustrated in Fig. 6 (top row). We conclude that the PSFs seem to degrade when the surface roughness has amplitude larger than approx. 2λ.

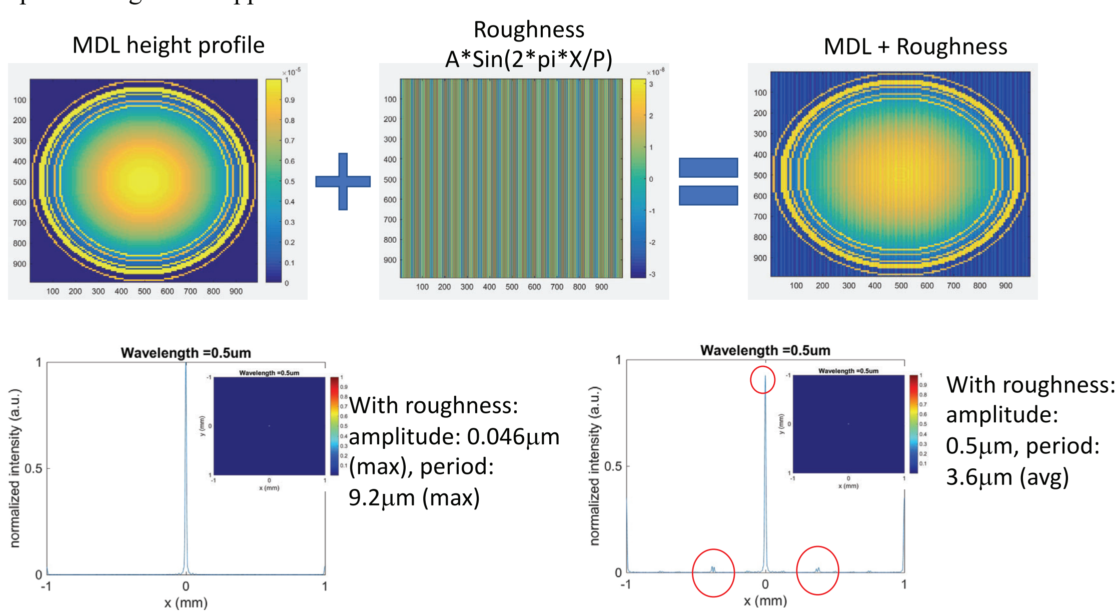


Fig. 6: Top: Modeling surface roughness (in 1 axis) using a small test MDL. Bottom: Simulated PSFs under 2 surface-roughness conditions.

**Impact of design approaches:**

We utilized the rotational symmetry of the problem to solve the scalar diffraction problem using the Hankel transform formulation, and then applied a gradient-assisted direct-binary search algorithm to create the design. The variables during optimization were the ring heights. The ring width was fixed at 5μm and the heights varied between 0 and 2.4μm. We assumed the dispersion properties of the Shipley 1813 photoresist. An improved figure of merit that attempts to minimize the difference between the Airy function and the simulated PSF, averaged all the wavelength samples gave the lowest background as illustrated in the simulated PSFs in Fig. 7.

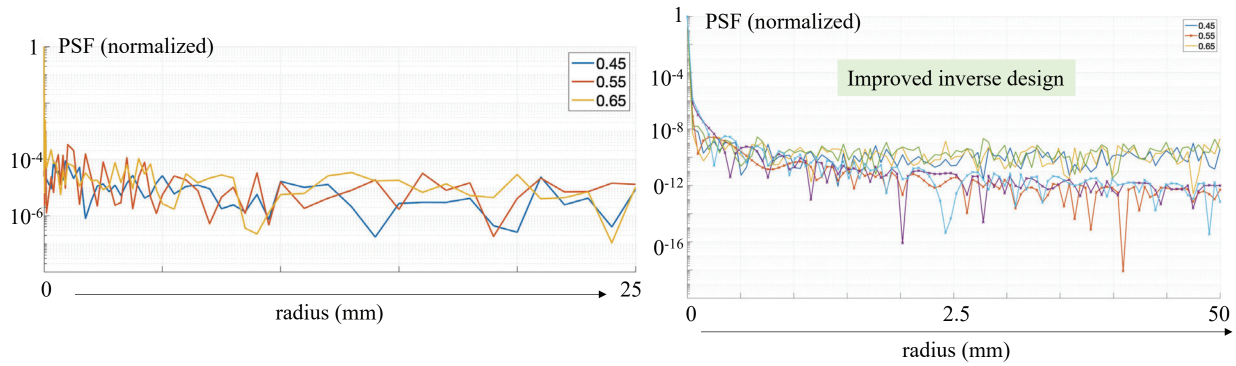


Fig. 7: By using an improved version of inverse design, it is possible to dramatically reduce the background in the PSF (and therefore, increase focusing efficiency). An example with a visible f/2 lens with focal length of 200mm is shown here. Left: maximizing wavelength averaged focusing efficiency. Right: minimizing difference from the corresponding Airy functions. The background is reduced by orders of magnitude. Three different wavelengths in the visible band are shown.

**Conclusions:**

Flat lenses provide an important toolbox for optical design with degrees of design freedom that are not accessible with conventional lenses. This technology has the potential to enable imaging systems that are not only lightweight, but also have functions that are not previously possible, such as ultra-broadband imaging through a single optical aperture.

## REFERENCES

[1] D. Chao, et al, "Immersion Zone-Plate-Array Lithography," J. Vac. Sci. Technol. B, 23(6), 2657-2661 (2005).
[2] M. Meem, et al, "Large-area, high-NA multi-level diffractive lens via inverse design," *Optica* 7(3) 252-253 (2020).
[3] M. Meem, et al, "Inverse-designed flat lens for imaging in the visible & near-infrared with diameter > 3mm and NA=0.3," *Appl. Phys. Lett.* 117(4) 041101 (2020).
[4] N. Mohammad, M. Meem, B. Shen, P. Wang and R. Menon, "Broadband imaging with one planar diffractive lens," *Sci. Rep. 8 2799* (2018).
[5] P. Wang, N. Mohammad and R. Menon, "Chromatic-aberration-corrected diffractive lenses for ultra-broadband focusing," *Sci. Rep.* 6, 21545 (2016).
[6] S. Banerji, et al, "Ultra-thin near infrared camera enabled by a flat multi-level diffractive lens," *Opt. Lett.* 44(22) 5450-5452 (2019).
[7] M. Meem, et al, "Imaging across the Short-Wave Infra-Red (SWIR) Band via a Flat Multilevel Diffractive Lens," *OSA Continuum* 2 (10) 2968-2974 (2019).
[8] M. Meem, et al, "Broadband lightweight flat lenses for longwave-infrared imaging," *PNAS* Oct 2019, 201908447.

[9] S. Banerji & B. Sensale-Rodriguez, "Inverse designed achromatic flat lens operating in the ultraviolet," *OSA Continuum* 3(7) 1917-1929 (2020).
[10] S. Banerji & B. Sensale-Rodriguez, "A computational design framework for efficient, fabrication error-tolerant, planar THz diffractive optical elements". Scientific reports, 9(1), 5801 (2019).
[11] M. Meem, A. Majumder and R. Menon, "Full-color video and still imaging using two flat lenses," *Opt. Exp.* 26(21) 26866-26871 (2018).
[12] M. Meem, et al, "Imaging from the visible to the longwave infrared via an inverse-designed flat lens," arXiv:2001.03684 (2020).
[13] S. Banerji, et al, "Diffractive flat lens enables Extreme Depth-of-focus Imaging," *Optica* 7(*3*) 214-2017 (2020).
[14] S. Banerji, M. Meem, B. Sensale-Rodriguez and R. Menon, "Imaging with flat optics: metalenses or diffractive lenses?," *Optica* 6(6) 805-810 (2019).