Extreme-depth-of-focus imaging with a flat lens: supplementary material

SOURANGSU BANERJI, 1, ¥ MONJURUL MEEM, 1, ¥ APRATIM MAJUMDER, 1 BERARDI SENSALÉ-RODRIGUEZ, 1 RAJESH MENON, 1, 2,*

1Department of Electrical and Computer Engineering, University of Utah, Salt Lake City, UT-84102, USA
2Oblate Optics, Inc., San Diego CA 92130, USA
*Corresponding author: rmenon@eng.utah.edu
¥ Equal contribution
Published 12 March 2020

This document provides supplementary information to "Extreme-depth-of-focus imaging with a flat lens," https://doi.org/10.1364/OPTICA.384164, including details on our literature survey as well as the EDOF MDL design, which were obtained using nonlinear optimization using a modified gradient-descent based search algorithm that maximized wavelength-averaged focusing efficiency. The PSF simulations were performed using commercially available FDTD software from Lumerical.

Comparison of Extended Depth of Focus Lenses

| Reference | Operating Wavelength | N.A. | DOF   | DOF/Operating wavelength | DOF/diffraction-limited DOF |
|-----------|----------------------|------|-------|--------------------------|-----------------------------|
| 1         | 10.6 um              | 0.05 | 40 mm | 3.77E03                  | 9.52                        |
| 2         | 10.6 um              | 0.05 | 37.6 mm | 3.55E03               | 8.95                        |
| 3         | 633 nm               | 0.0321 | 100 mm | 1.58E05              | 162.7820                    |
| 4         | 633 nm               | 0.95 | 4.84 um | 7.65                   | 6.9002                      |
| 5         | 633 nm               | 0.1724 | 1 mm   | ~1.58E03               | 46.9538                     |
| 6         | 850 nm               | 0.45 | 2.5 mm | ~2.95E03               | 595.5885                    |
| 7         | 10.6 um              | 0.0504 | 50 mm | ~4.717E03               | 11.9819                     |
| 8         | 633 nm               | 0.93 | 3.16 um | ~5                     | 4.3177                      |
| 9         | 405nm                | 0.95 | 4 um | ~10                     | 8.9136                      |
| 10        | 1 mm                 | 0.5  | 248 mm | 248                   | 62                          |
| 11        | 1 mm                 | 0.6061 | 100 mm | 100                 | 36.7357                     |
| 12        | 0.5 mm               | 0.7  | 10 mm  | 20                     | 9.8                         |
| 13        | 1 mm                 | 0.4472 | 100 mm | 100                 | 19.9988                     |
| 14        | 3 mm                 | 0.67 | 70mm   | ~23.33             | 10.4478                     |
| 15        | 0.6mm                | 0.5812 | 31.3mm | ~52.17             | 17.6216                     |
| 16        | 1.5 mm               | 0.9659 | 48.6mm | ~32.4             | 30.2280                     |
| 17        | 405nm                | 1.2  | 4.05um | 10                  | 14.4                        |
1. Measured Point Spread Function (PSF)

Some of the measured point spread functions (PSFs) for the designed MDLs are provided below:

(5mm – 1200 mm):

![PSF Images]

2. Efficiency Spectra

3. Fabrication

The MDL depicted was patterned in a photoresist (Microchem, S1813) film atop a glass wafer (thickness ∼ 0.6 mm) using grayscale laser patterning with a Heidelberg Instruments MicroPG101 tool [21-23]. In such conventional gray-scale lithography, the write head scans through the sample surface and the exposure dose at each point is modulated with different gray-scales [21, 22] (see schematic illustration of Fig. S3). Most of these typical photoresists are characterized by a contrast curve. Different depths in accord with different exposure doses are achieved after development. Greater dose leads to deeper feature. Before patterning structures, it is needed to calibrate this contrast curve. In this case, too, the exposure dose was varied with respect to position to achieve the multiple height levels dictated by the design.

![Fabrication Illustration]

4. Experiment details (focal spot characterization)

The flat lenses were illuminated with expanded and collimated beam from the SuperK VARIA filter (NKT Photonics). The wavelength and bandwidth can be changed using the VARIA filter [24]. The focal planes of the MDLs were magnified using an objective (RMS20X-PF, Thorlabs) and tube lens (ITL200, Thorlabs) and imaged onto monochrome sensor (DMM 27UP031-ML, Imaging Source). The gap between objective and tube lens was ∼90 mm and that between the sensor and the backside of tube lens was
about 148 mm. The magnification of the objective-tube lens was 22.22X.

Fig. S4: Schematic of system used for focusing experiments.

After capturing the focal spot, the focusing efficiency was then calculated using the following equation: Focusing efficiency = (sum of pixel values in 3*FWHM) / (sum of pixel values in the entire lens area)

5. Image characterization

The flat lenses were used for imaging the object on to the sensor. The experimental setup is shown in Fig. S5 for both MDLs. The exposure time was adjusted to ensure that the images were not saturated. In each case, a dark frame was recorded and subtracted from the obtained images. For imaging, the objects were placed in front of the MDL. However, this time the objects were illuminated with both IR LEDs and IR floodlights to cover the entire range and the corresponding images were captured using a monochrome sensor (DMM 27UP031-ML, Imaging Source). The Field of View (FOV) for the MDL in both the vertical (Fig. S5 (a)) and horizontal direction (Fig. S5 (b)) was calculated using trigonometry after noting down the appropriate distances. The distances were ascertained up to which the image was relatively sharp as seen with the naked eye. In addition, we measured the MTF as a function of incident angle as illustrated in Fig. S8.

Fig. S5: Experimental setup of image characterization for calculating the FOV of MDL in (a) vertical direction (1st shot) and (b) horizontal (2nd shot). (c) Experimental setup of image characterization for the depth of field of the MDL.

The following supplementary videos are also included:
1. EDOF_imaging_1: imaging stationary objects, keeping everything in focus.
2. EDOF_imaging_2: imaging stationary objects with 1 object in motion, keeping everything in focus.

6. Resolution from the USAF 1951 chart

Resolution test targets are typically used to measure the resolution of an imaging system. They consist of reference line patterns with well-defined thicknesses and spacing, which being designed to be kept in the same plane as the object being imaged. By identifying the largest set of non-distinguishable lines, one determines the resolving power of a given system. The R3L3S1N from Thorlabs (as used here) negative target uses chrome coating to cover the substrate, leaving the pattern itself clear, and works well in back-lit and highly illuminated applications.

Fig. S6: (a) Resolution Target Chart USAF 1951 (b) Resolution Characterization chart for the resolution target.

Because these targets feature sets of three lines, they reduce the occurrence of spurious resolution and thus help prevent inaccurate resolution measurements.

7. Modulation Transfer Function (MTF)

The average MTF at 10% contrast for the MDL is ~23 lp/mm over the entire range.

Fig. S7: Modulation Transfer Function for the MDL.
Fig. S8: Modulation Transfer Function for the MDL at a fixed distance of \( f = 5 \) mm as a function of the incident angle. The corresponding PSFs are shown in the bottom panels.

8. Raw Images of the US Air Force resolution chart

U fixed and V varied

U fixed at 50mm

U fixed at 100mm

V fixed and U varied

V fixed at 7mm

V fixed at 200mm

Fig. S9: Resolution Chart images for fixed object distance at 50mm and 100mm and varied image distance

Fig. S10: Resolution Chart images for fixed object distance at 200mm and varied image distance

Fig. S11: Resolution Chart images for fixed image distance at 7mm and 20mm and varied object distance
9. Image taken with a Google Pixel 3 mobile camera

![Figure S12: Resolution Chart images for fixed image distance at 50mm and 100mm and varied object distance](image)

Fig. S12: Resolution Chart images for fixed image distance at 50mm and 100mm and varied object distance

![Figure S13: Exemplary image taken with a Google Pixel 3 mobile camera keeping the objects in a relatively similar object distance as show in Fig. 5(c) of the main manuscript](image)

Fig. S13: Exemplary image taken with a Google Pixel 3 mobile camera keeping the objects in a relatively similar object distance as show in Fig. 5(c) of the main manuscript.

11. Comparison of EDOF MDL with conventional diffractive (Fresnel) lenses

To compare the EDOF MDL with regular diffractive lens, we have fabricated two Fresnel lens (FL) naming FL1 and FL2, having the same diameter as the EDOF MDL but each with a fixed focal length. The focal lengths of the FL1 and FL2 are 602.5mm and 100mm, respectively. The optical micrographs of the Fresnel lenses are shown in Fig. S14.

![Fig. S14: Optical micrographs of the Fresnel lenses (focal length left = 602.5mm, right =100mm).](image)

The measured PSFs of FL1 and FL2 at their respective focal lengths and a few other exemplary distances are presented in Figure S14. The PSF of the EDOF MDL is also shown for reference.
The XZ sections of the PSFs as a function of z is given in Figure S15.

Fig. S16: Measured intensity distribution at the YZ plane for the EDOF MDL, FL1 and FL2.

We have also repeated Figure 3 and Figure 4 from the main text with the FL1 and FL2; the results are given in Fig. S16 and Fig. S17.

Fig. S17: Imaging with BDL and FL at different object distances without refocusing. The value of \( v \) is fixed for each row and value of \( u \) is noted in parenthesis in each image.

Fig. S18: Imaging with BDL and FL at different object distances without refocusing. The value of \( u \) is fixed for each row and value of \( v \) is noted in parenthesis in each image.
12. EDOF vs Reference aperture

We have also measured the diffraction pattern of a reference aperture having same diameter as the EDOF MDL. The cross section of the intensity patterns as a function of distance (z) is given in Fig. S18, the corresponding EDOF MDL values are also plotted for reference.

Fig. S19: Measured intensity distribution at the YZ plane for the EDOF MDL and a reference aperture of same diameter.

REFERENCES

1. Z. Liu, A. Flores, M. R. Wang, and J. J. Yang, “Infrared imaging lens with extended depth of focus,” Proc. SPIE 5783, 841–848 (2005).
2. Z. Liu, A. Flores, M. R. Wang, and J. J. Yang, “Diffractive infrared lens with extended depth of focus.” Optical Engineering, 46(1), p.018002 (2007).
3. J. Sochacki, A. Kołodziejczyk, Z. Jaroszewicz, and S. Bará, “Nonparaxial design of generalized axicons.” Appl. Opt. 31, 5326-5330 (1992).
4. G. H. Yuan, S. B. Wei, and X.-C. Yuan, “Nondiffracting transversally polarized beam.” Opt. Lett. 36, 3479-3481 (2011).
5. M. A. Golub, V. Shurman, and I. Grossinger, “Extended focus diffractive optical element for Gaussian laser beams.” Appl. Opt. 45, 144-150 (2006).
6. Q.Q. Zhang, J.G. Wang, M.W. Wang, J. Bu, S.W. Zhu, R. Wang, B.Z. Gao, and X.C. Yuan, “A modified fractal zone plate with extended depth of focus in spectral domain optical coherence tomography.” Journal of Optics, 13(5), p.055301 (2011).
7. L. Shi, X. Dong, Q. Deng, Y. Lu, Y. Ye, and C. Du, “Design and characterization of an axicon structured lens.” Optical Engineering, 50(6), p.063001 (2011).
8. A.P. Yu, G. Chen, Z.H. Zhang, Z.Q. Wen, L.R. Dai, K. Zhang, S.L. Jiang, Z.X. Wu, Y.Y. Li, C.T. Wang, and X.G. Luo, “Creation of sub-diffraction longitudinally polarized spot by focusing radially polarized light with binary phase lens.” Sci. Rep., 6, p.38859 (2016).
9. G. Yuan, E.T. Rogers, T. Roy, G. Adamo, Z. Shen, and N.I. Zheludev, “Planar super-oscillatory lens for sub-diffraction optical needles at violet wavelengths.” Sci. Rep., 4, p.6333 (2014).
10. X. Wei, C. Liu, L. Niu, Z. Zhang, K. Wang, Z. Yang, and J. Liu, “Generation of arbitrary order Bessel beams via 3D printed axicons at the terahertz frequency range.” Opt. Lett. 54, 10641-10649 (2015).
11. C. Liu, L. Niu, K. Wang, and J. Liu, “3D-printed diffractive elements induced accelerating terahertz Airy beam,” Opt. Express 24, 29342-29348 (2016).
12. X.-Y. Jiang, J.-S. Ye, J.-W. He, X.-K. Wang, D. Hu, S.-F. Feng, Q. Kan, and Y. Zhang, “An ultrainfrared terahertz lens with axial long focal depth based on metasurfaces,” Opt. Express 21, 30030-30038 (2013).
13. J. Liu, L. Wang, J. Li, W. Wang, and Z. Hong, “Large focal depth of THz imaging system based on quasi-Bessel beams.” In Infrared, Millimeter Wave, and Terahertz Technologies (Vol. 7854, p. 785422). International Society for Optics and Photonics (2010).
14. S. Monk, J. Arit, D.A. Robertson, J. Courtial, and M.J. Padgett, “The generation of Bessel beams at millimetre-wave frequencies by use of an axicon.” Optics Communications, 170(4-6), pp.213-215 (1999).
15. Z. Zhang, and T. Buma, “Terahertz imaging in dielectric media with quasi-Bessel beams.” In Terahertz Technology and Applications IV (Vol. 7938, p. 793806). International Society for Optics and Photonics (2011).
16. G. Ok, S.W. Choi, K. Park, and H. Chun, “Foreign object detection by sub-terahertz quasi-Bessel beam imaging.” Sensors, 13(1), pp.71-85 (2013).
17. K.B. Rajesh, Z. Jaroszewicz, P.M. Anbarasan, T.V.S. Pillai, and N.V. Suresh, “Extending the depth of focus with high NA lens axicon.” Optik-International Journal for Light and Electron Optics, 122(18), pp.1619-1623 (2011).
18. M. Veyssi, C. Guclu, O. Boyraz, and F. Capolino, “Reflective metasurface lens with an elongated needle-shaped focus,” J. Opt. Soc. Am. B 34, 374-382 (2017).
19. H. Wang, L. Shi, B. Lukyanchuk, C. Sheppard, and C.T. Chong, “Creation of a needle of longitudinally polarized light in vacuum using binary optics.” Nature Photonics, 2(8), p.501 (2008).
20. S.F. Busch, G.E. Town, M. Scheller, and M. Koch, M., “Focus free terahertz reflection imaging and tomography with Bessel beams.” Journal of Infrared, Millimeter, and Terahertz Waves, 36(3), pp.318-326 (2015).
21. McKenna, Curt, Kevin Walsh, Mark Crain, and Joseph Lake. ”Maskless Direct Write Grayscale Lithography for MEMS Applications.” In Micro/Nano Symposium (UGIM), 2010 18th Biennial University/Government/Industry, pp. 1-4. IEEE, (2010).
22. Wang, Peng, Jose A. Dominguez-Caballero, Daniel J. Friedman, and Rajesh Menon. “A new class of multi-bandgap high-efficiency photovoltaics enabled by broadband diffractive optics.” Progress in Photovoltaics: Research and Applications 23, no. 9: 1073-1079 (2015).
23. Data sheet of Heidelberg µPG 101: http://www.himt.de/index.php/upg-101.html
24. Data sheet of SuperK Varia Filter: http://www.nktphotonics.com/wp-content/uploads/2015/03/SuperK_VARIA.pdf