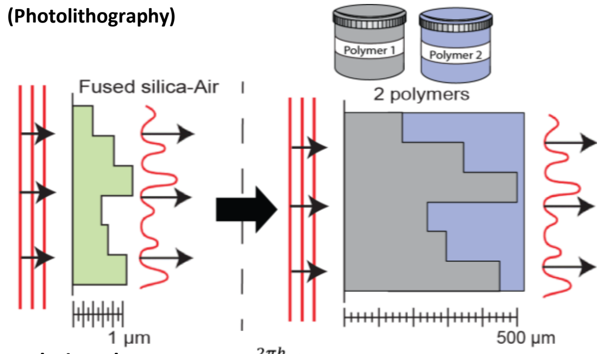
3D printing-based fabrication of diffractive optical elements by liquid immersion or near-index-matched materials

Reut Orange-Kedem, Elias Nehme, Lucien E. Weiss, Boris Ferdman, Onit Alalouf, Nadav Opatovski, and Yoav Shechtman
Technion Israel institute of technology, Haifa, Israel

Abstract: Diffractive optical elements (DOEs) are used to shape the wavefront of incident light. This can be used to generate practically any pattern of interest, albeit with varying efficiency. A fundamental challenge associated with DOEs comes from the nanoscale-precision requirements for their fabrication. Here we demonstrate a method to controllably scale up the relevant feature dimensions of a device from tens-of-nanometers to tens-of-microns by using near-index-matched materials. This makes it possible to utilize modern 3D-printing technologies for fabrication, thereby significantly simplifying the production of DOEs and decreasing costs by orders of magnitude, without hindering performance. We demonstrate the tunability of our design for varying experimental conditions, and the suitability of this approach to ultrasensitive applications by localizing the 3D positions of single molecules in cells using our microscale fabricated optical element to modify the point spread-function (PSF) of a microscope. **Furthermore, we have fabricated a variety of elements that show the versatility of our fabrication method in different fields requiring DOEs.**

The concept: By using near-index-matched materials we decrease the refractive indices difference. Subsequently, for maintaining the desired relative phase, pixel height needs to increase, respectively. This means that we effectively increase the DOE dimension from the nano to the micro scale[1].

Standard Fabrication method: (Photolithography) **The 2-material immersed DOE:**



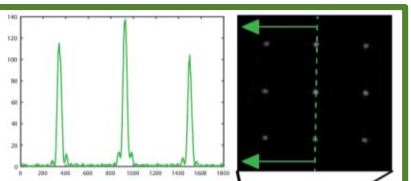
Relative phase: $\Delta\phi = \frac{2\pi h}{\lambda}(n_{Polymer1} - n_{Polymer2})$

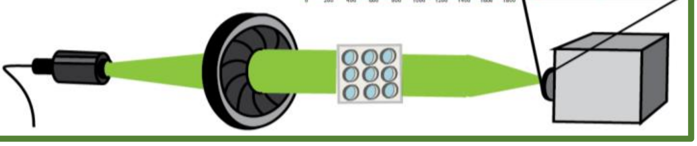
Where, λ is the wavelength, h is the pixel height and n is the refractive index

Scale up DOE dimensions ➔
Scale up the robustness to fabrication error

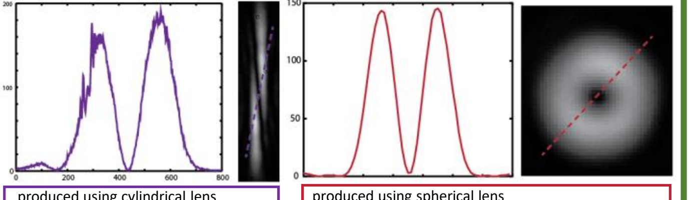
Applications:

Micro-lens array ➔ Light focusing





Spiral phase plates ➔ transforms an incident Gaussian laser beam profile to a donut-shaped intensity ring with zero intensity at the center

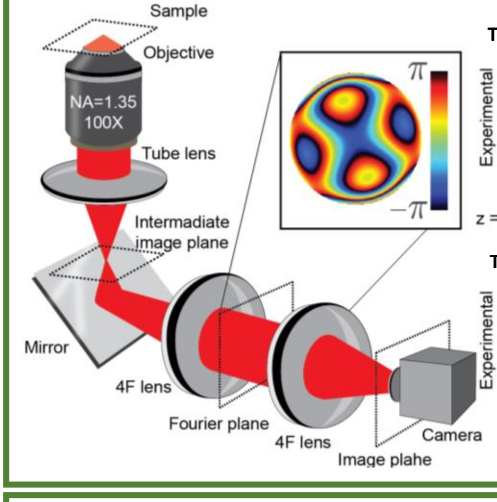


produced using cylindrical lens
For measuring the topological charge

produced using spherical lens
For measuring the donut-shaped profile

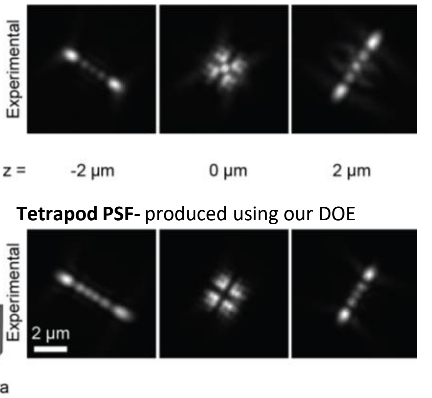
In our method we can easily change the topological charge or readjust the SPP To different wavelength by slightly changing the properties of the second polymer!

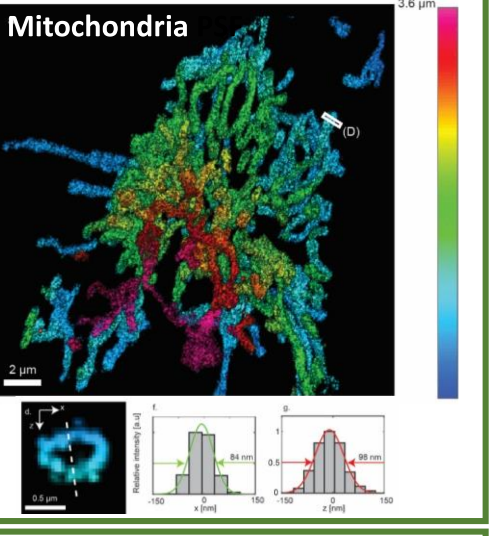
3D super resolution microscopy by point-spread function(PSF) engineering [2,3]



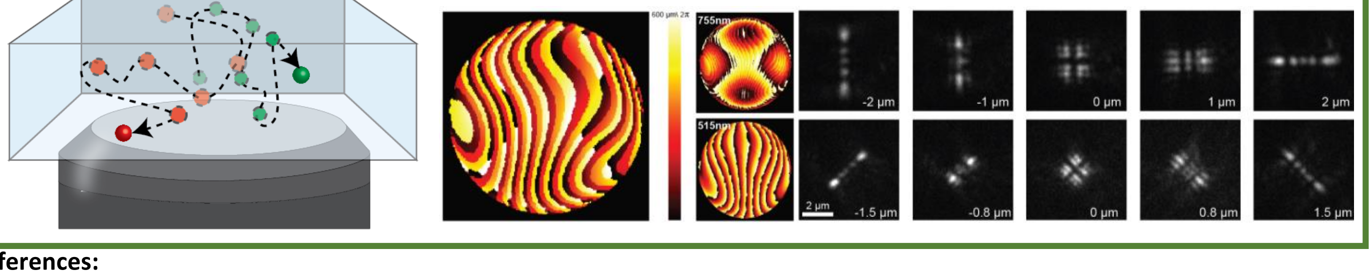
Tetrapod PSF- produced using lithography DOE

Tetrapod PSF- produced using our DOE





Multi - color elements ➔ different PSFs for different wavelengths in a single element. Color encoded by PSF rotation



References:

1. R. orange-Kedem et al, *"3D printable diffractive optical elements by liquid immersion"*,Nature communications
2. Shechtman, Yoav, et al. "Precise three-dimensional scan-free multiple-particle tracking over large axial ranges with tetrapod point spread functions." *Nano letters* 15.6 (2015): 4194-4199
3. *Nehme, E. et al. DeepSTORM3D: dense 3D localization microscopy and PSF design by deep learning. Nat. Methods 17, 734–740 (2020).*