# Imaging with Diffractive Axicons rapidly milled on Sapphire by Femtosecond Laser Ablation

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- Single pulse burst femtosecond laser fabrication will produce a flatter and smoother profile of axicons milled on sapphire compared to a pulse overlapped fabrication which will result in a damaged and a much rougher surface.
- The fabrication of large area (sub-1 cm cross-section) micro-optical components in a short period of time (~ 10 min) and with lesser number of processing steps is highly desirable and cost-effective.
- We show manufacturing of three configurations the conventional axicon, a photon sieve axicon (PSA) and a sparse PSA directly milled onto a sapphire substrate.
- Debris was removed using IsoPropyl alcohol and potassium hydroxide and amorphous sapphire was redeposited under incoherent illumination to test the components for optical viability.
- A non-linear optical filter was used for cleaning noisy images which were generated by diffractive optical elements.

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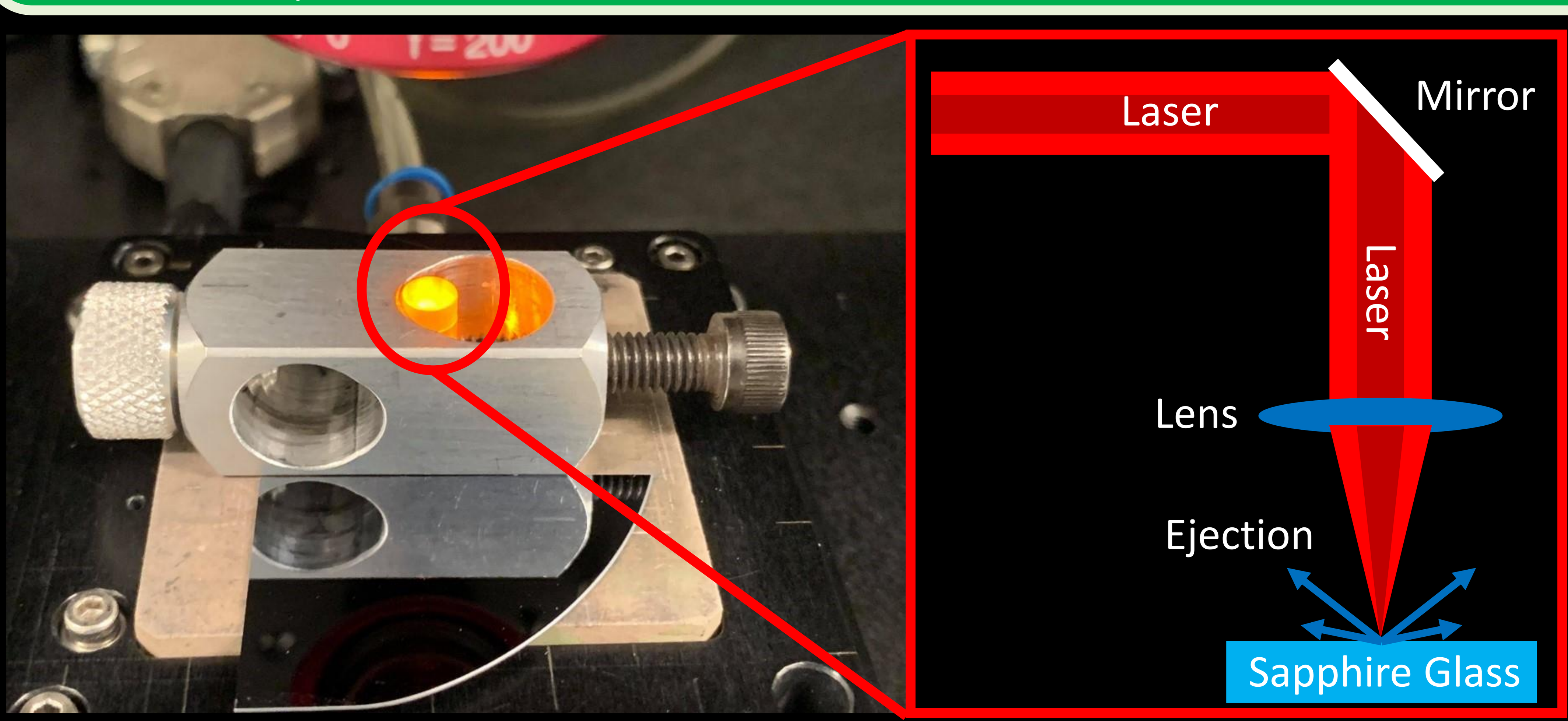
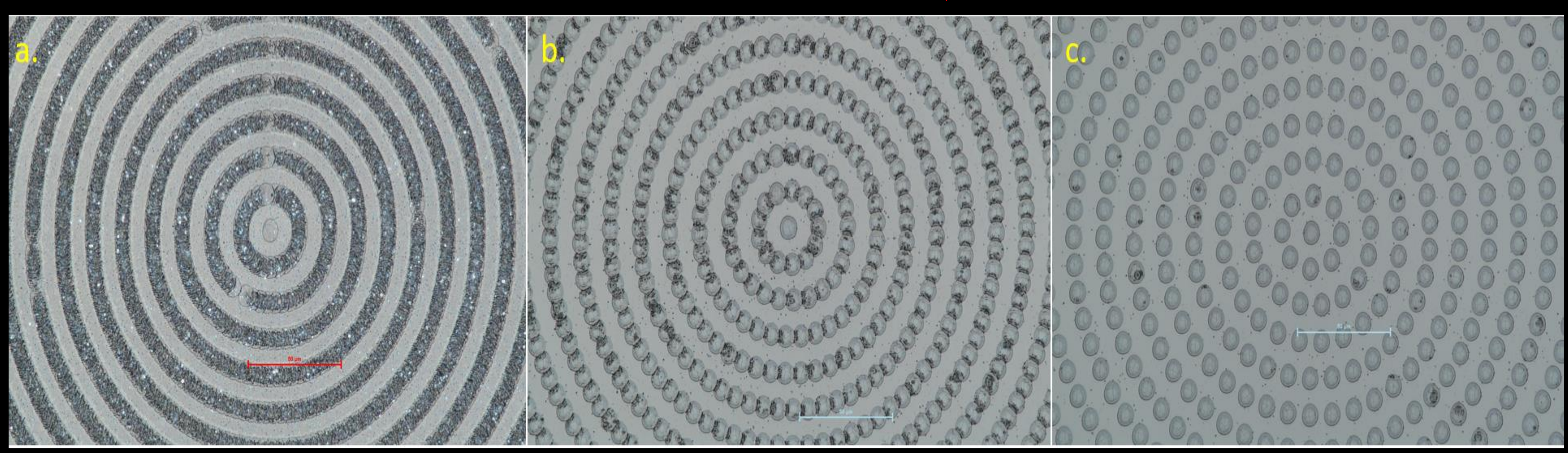
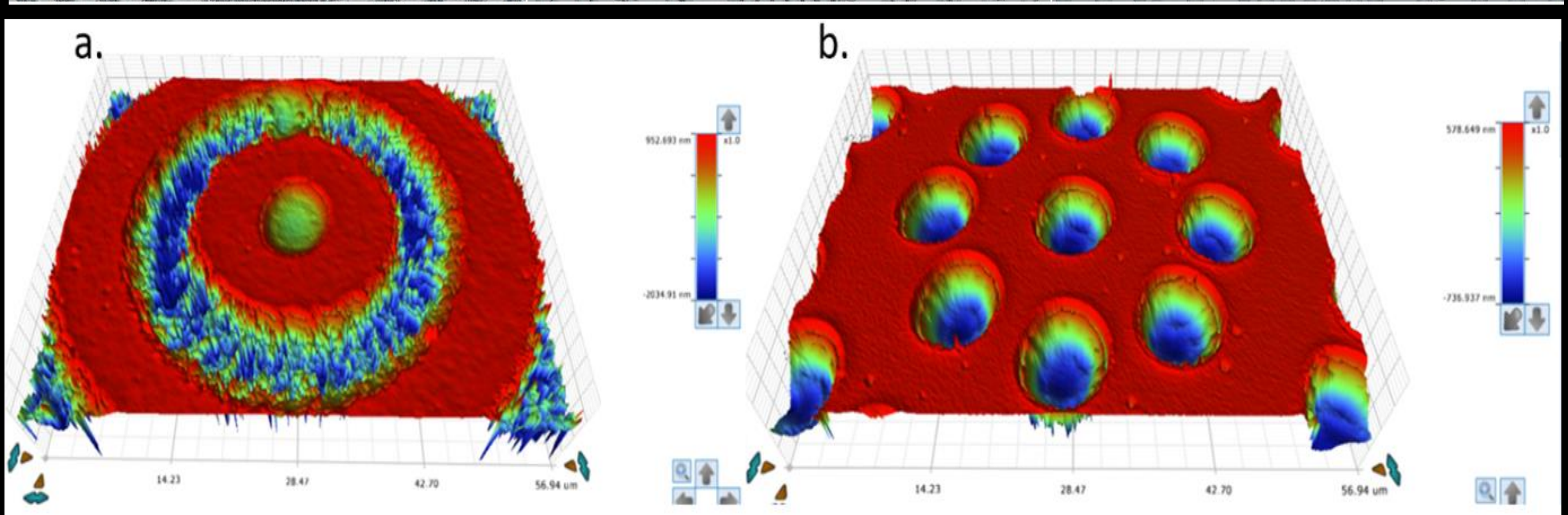
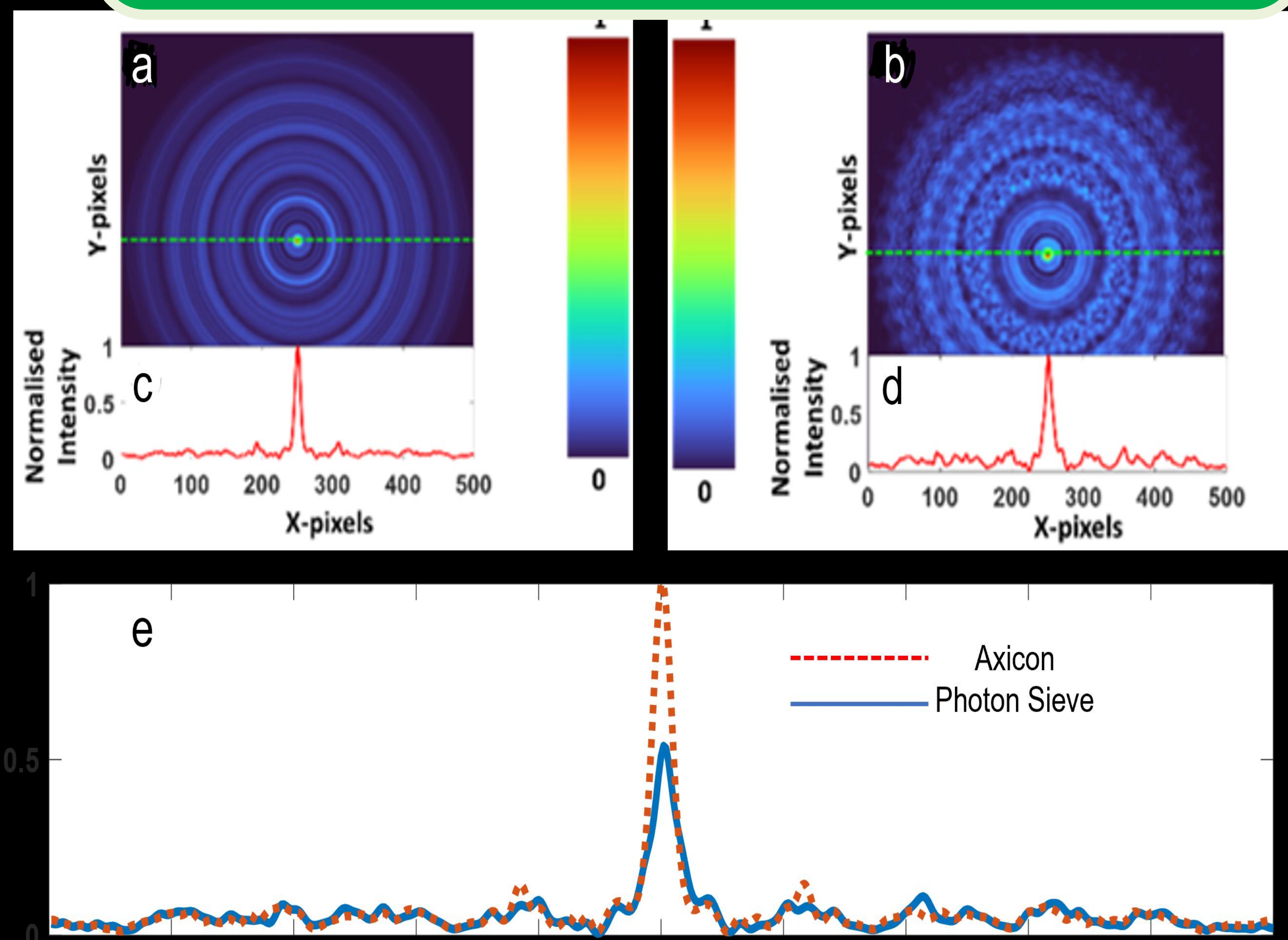



- PHAROS Laser (from Light Conversion, Lithuania)
- Conditions: 200kHz, λ = 1030nm, 2.5W average power, 230fs pulse duration, and Mitutoyo Plan Apo NIR infinity corrected objective lens (0.14NA)
- Two pulse bursts per ablation spot (with an exception for the axicon that did not use a pulse burst)
- Conditions on Sample: Attenuated to 5 µJ to achieve the design ablation depth, spot diameter of d=8.9 µm, and Pulse energy of 69 TW/cm$^2$ at a fluence of 16 J/cm$^2$
- This is markedly larger than the ablation threshold of sapphire at ~2 J/cm$^2$ and ~10 TW/cm$^2$.



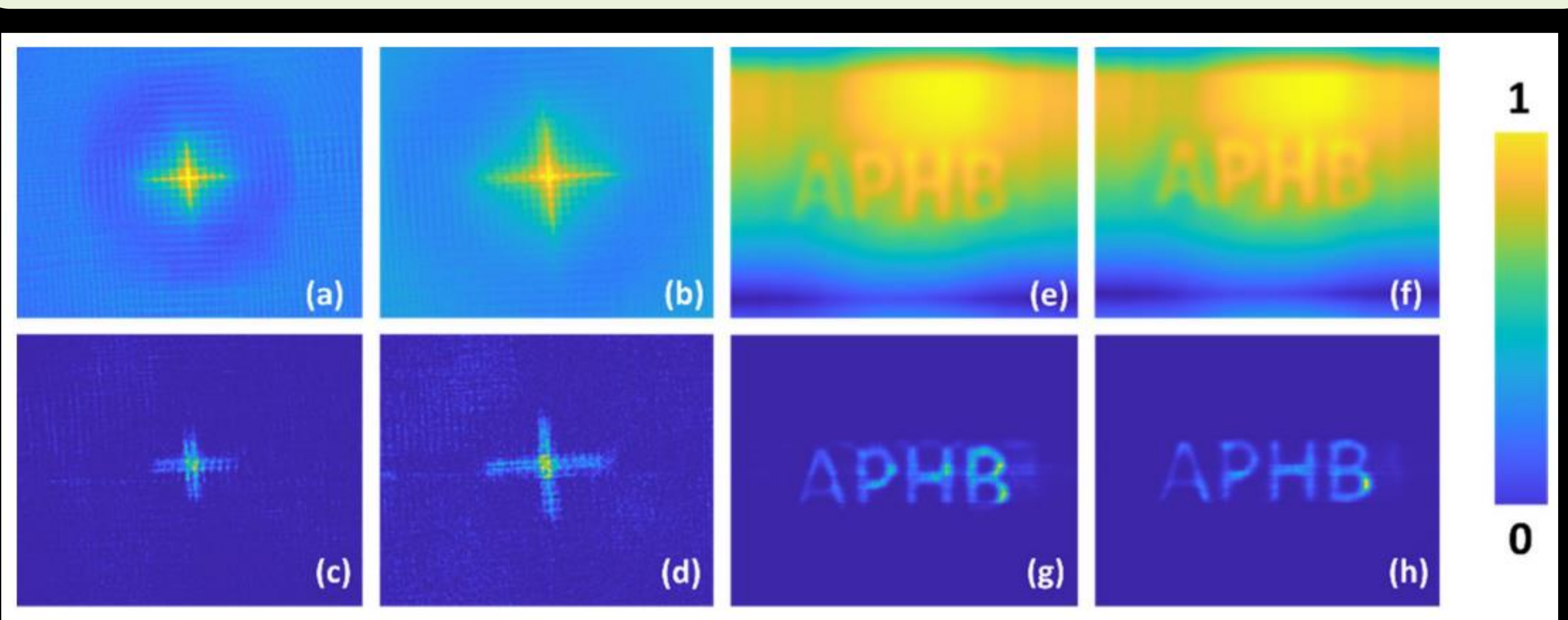




- Optical microscope images of the axicon (a), PSA (b), and sparse PSA (c).
- The axicon image (a), there are stitching errors which were later fixed.
- Optical Profilometer results of the axicon (a) and the sparse PSA (b).
- Depth of ablation was 360 nm for the axicon and 420 nm for the sparse PSA.
- Axicon has a very binary (two step) level to it while the sparse PSA has a more gaussian shape to each pulse.
- In the cases where multiple bursts were used the holes of the axicons and PSA's contained ripple artifacts.

- Intensity distribution obtained for an axicon (a) and PSA (b) with their corresponding locally normalised intensity profiles of the line data (c) and (d).
- Comparison of universally normalised intensity profile of the line data for both axicon and PSA (e).
- Intensity pattern observed at a distance v from the diffractive optical element is given as a convolution of the complex amplitude with the quadratic phase function Q(1/v):

$$I_v(\bar{r_s};\bar{r_0},u) = \left|C_1\sqrt{I_0}L\left(\frac{\bar{r_0}}{u}\right)Q\left(\frac{1}{u}\right)e^{-j(\Phi_{DOE})}\otimes Q\left(\frac{1}{v}\right)\right|^2$$




- The fabrication time was only 10 min using the femtosecond fabrication method for a large area of 5 mm × 5 mm.
- The method of fabrication enhanced imaging capabilities and we believe this direction of research will enable the fabrication of large area structures suitable for incoherent illumination and astronomical imaging applications.