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High resolution 3D printing with a low NA focal lens

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XXL & SIOM & ECNU

Two connected stories:

1. **3D microprinting of macroscale objects in polymer;**

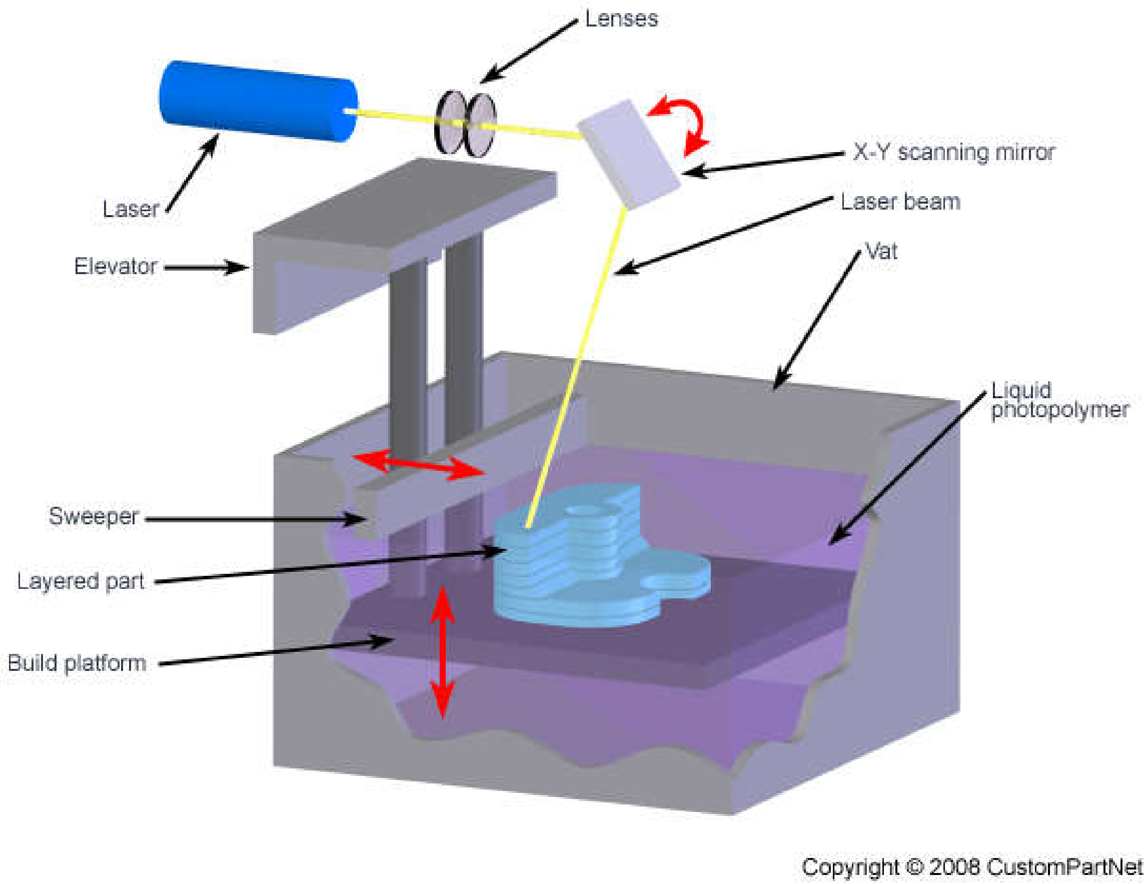
2. **3D printing in glass without optical aberration.**

Two connected stories:

1. **3D microprinting in polymer with heights above 1 cm;**

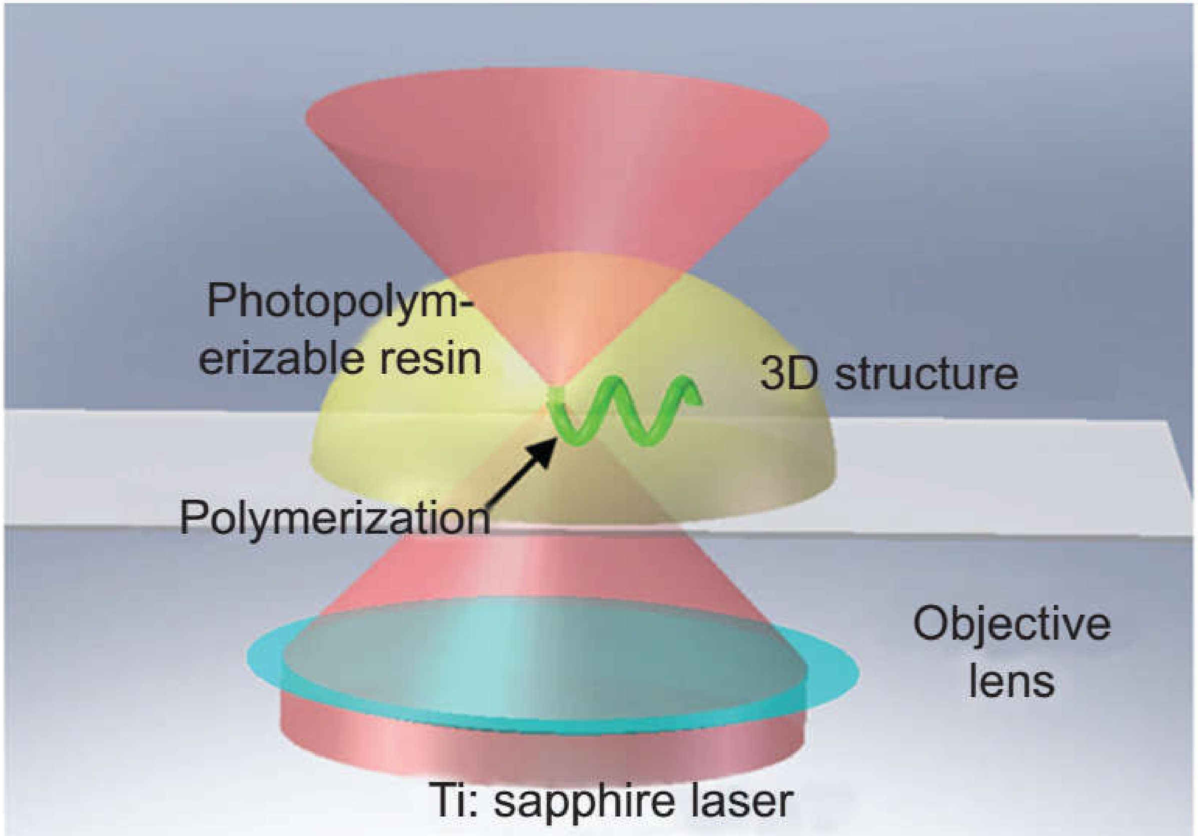
2. **3D microprinting in glass without optical aberration *(physics to be identified).***

High resolution 3D printing today: layer-by-layer



Limit of resolution: ~20 μm limited by the absorption depth of UV light
Size of structure: unlimited height and area size in principle

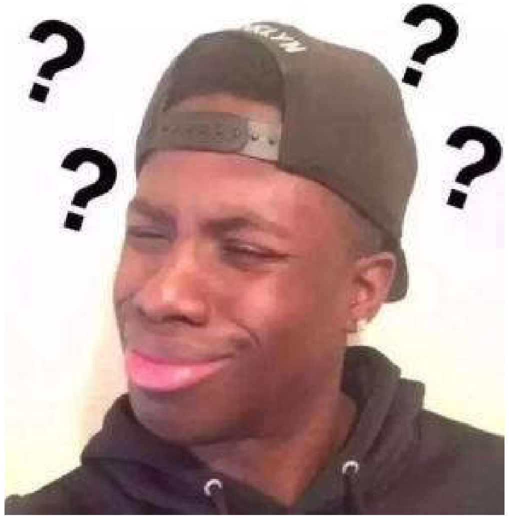
High resolution 3D printing today: two photon polymerization



Nanoscribe, Germany

Limit of resolution： ~100 nm by the threshold effect (Nanoscribe, Germany)
Size of structure： << 1 mm limited by the working distance of focal lens

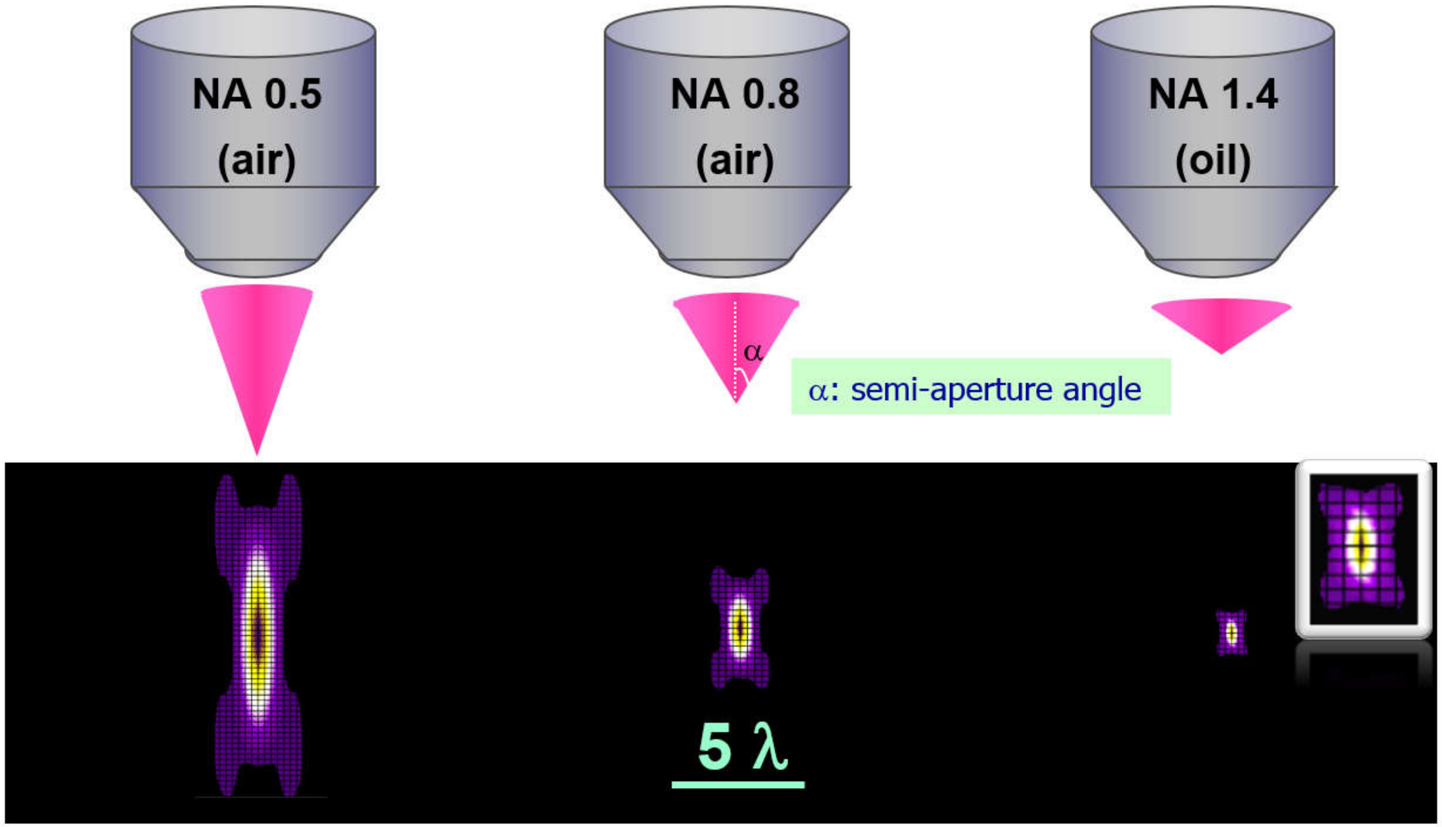
We have a problem…*big problem!*



Layer by layer UV polymerization：
Large but rough

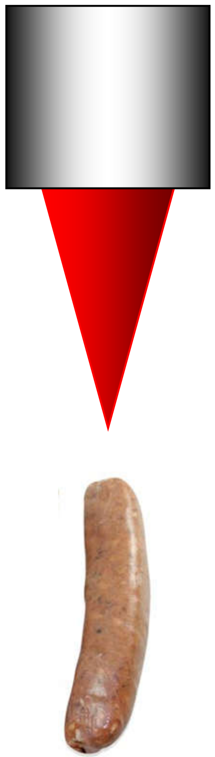
Two photon polymerizaton：
Fine but small

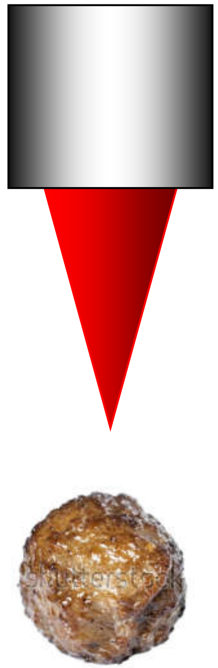
Two photon polymerization：why short working distance?



Low numerical aperture (NA) leads to low ***axial*** resolution !
High NA lens of ***short working distance*** is a MUST!

Manipulating light: how to produce a spherical spot?

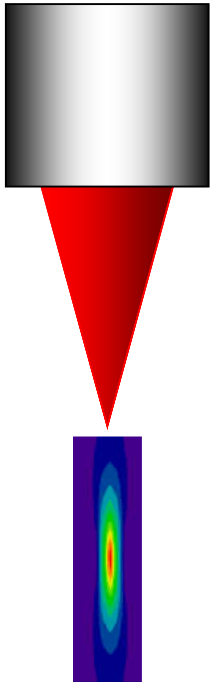




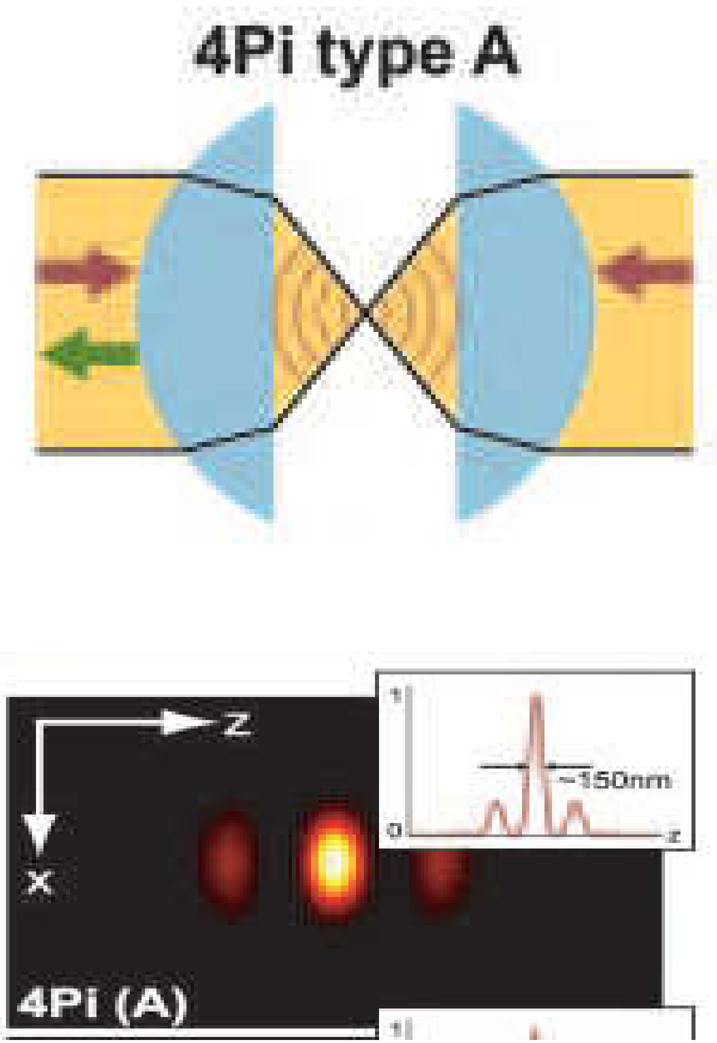
Conventional focusing:
Elongated sausage spot

New focusing scheme:
Spherical meat-ball spot

An old problem: how to produce a spherical focal spot?
Of interest to both microscopy and micromachining

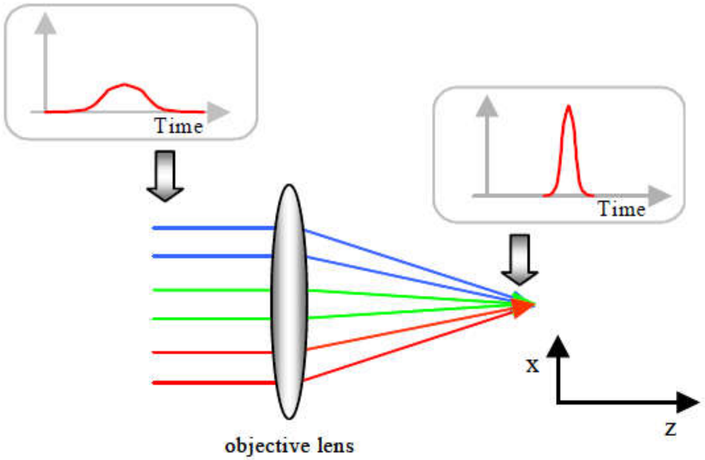


A focal spot always has an ellipsoidal shape elongated along the optical axis!

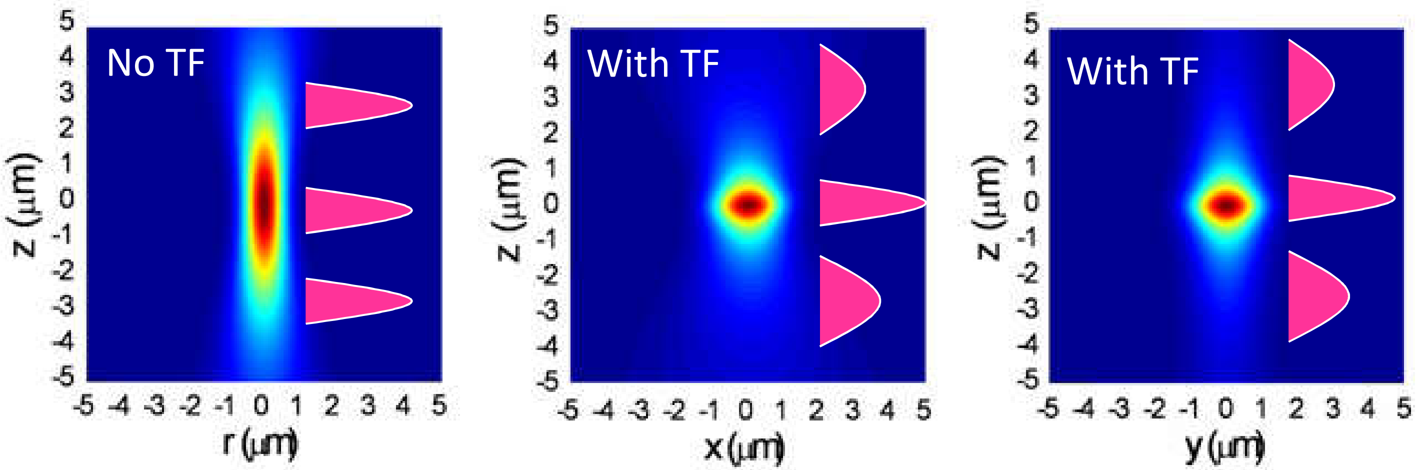


Stephan Hell (mainly focusing on superresolution microscopy) once overcome this issue with a 4 Pi focusing scheme, in which two face-to-face high-NA lenses are used. Therefore, 4pi focusing is impractical for materials processing.

3D spherical focal spot – the nonlinear magic of short pulses



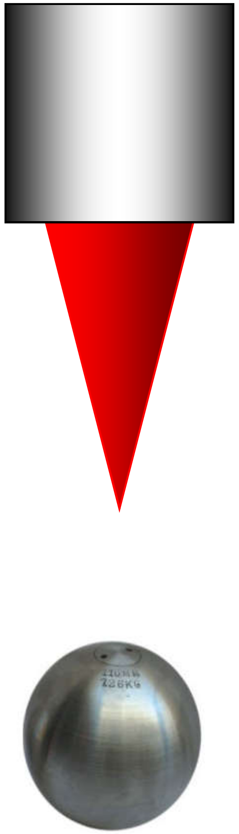
F. He et. al., Opt. Lett. 35, 1106 (2010)



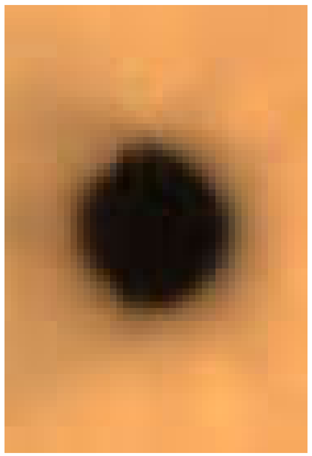
We realize that temporal focusing uniquely allows us to produce a 3D isotropic focal spot, in a nonlinear way!

*The **new** problem: how to produce a spherical spot **at low NAs** ?*

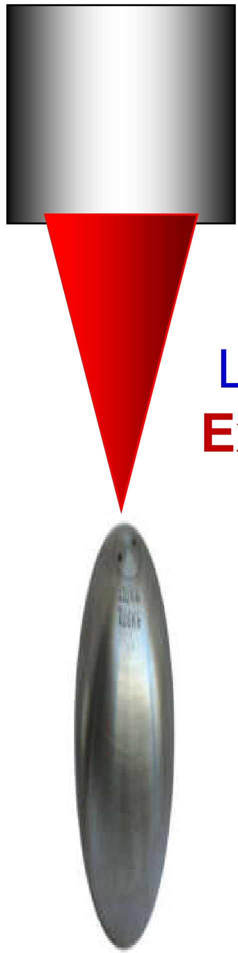
Spatiotemporal: NA 0.013



Transverse: 80 µm
Longitudinal: 80 µm
Fully spherical



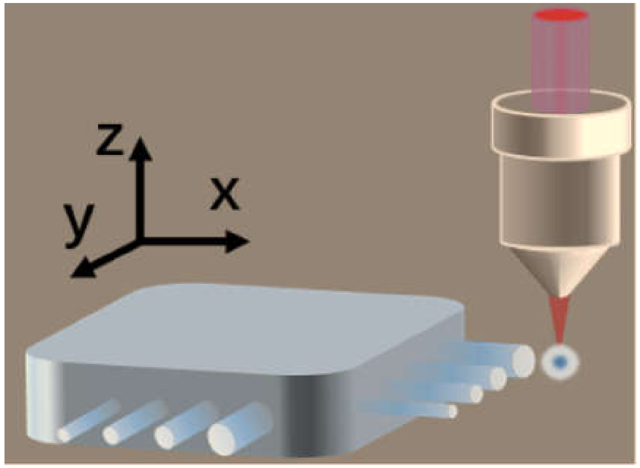
Conventional: NA 0.013



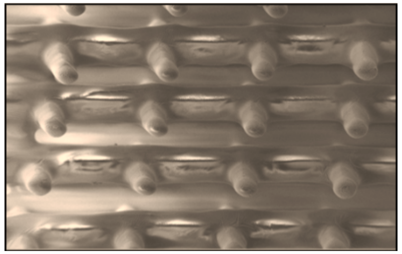
Transverse: 32 µm
Longitudinal: 850 µm
Extremely ellipsoidal

Y. Tan, et. al., Opt. Mater. Express 6, 3787-3793 (2016)

Tuning of 3D isotropic resolution by varying the laser power

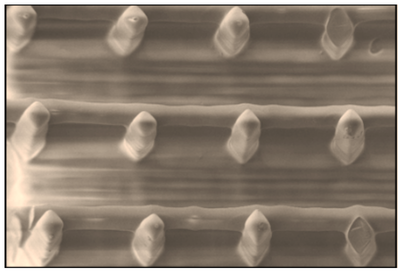


Rods in X direction and Y direction with different laser powers



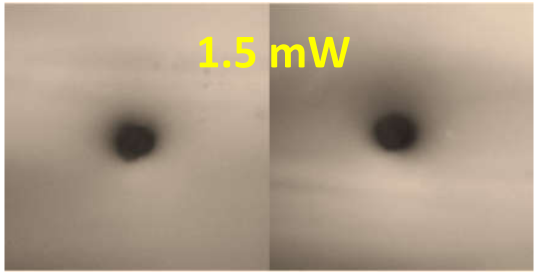
SEM pictures
Of the rods

3 mW

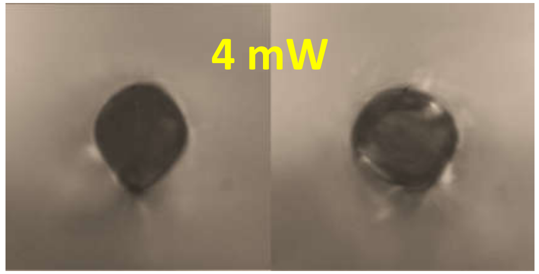


6 mW

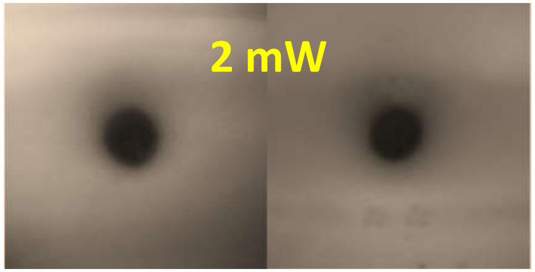
XZ	YZ	XZ	YZ



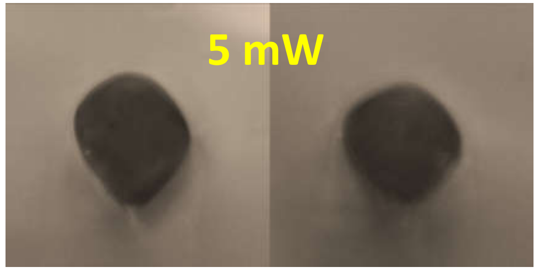
xy: 9 um z: 9um



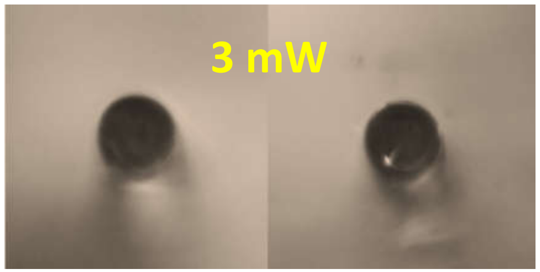
xy: 27 um z: 27 um



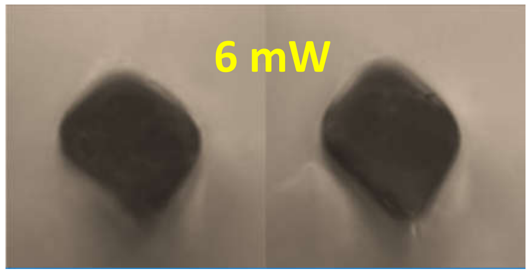
xy: 14 um z: 14 um



xy: 32 um z: 35 um

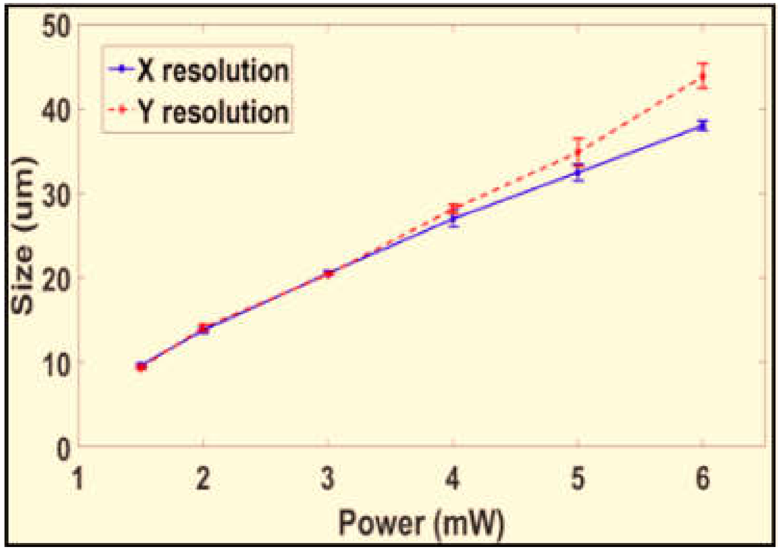


xy: 20 um z: 20 um

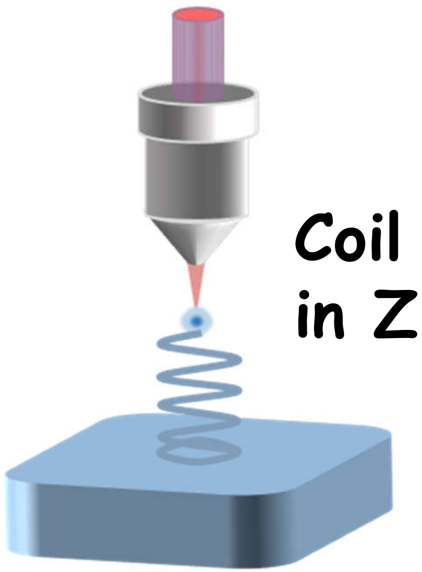


xy: 38 um z: 44 um

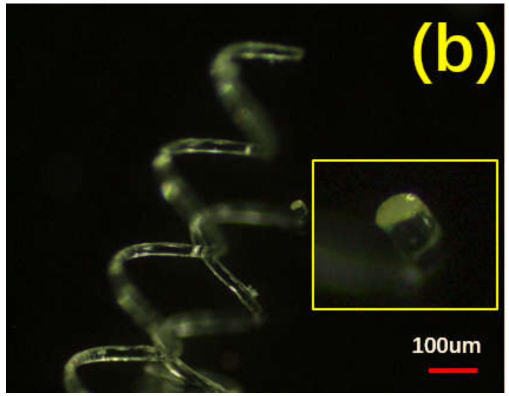
Tuning of 3D isotropic resolution by varying the laser power



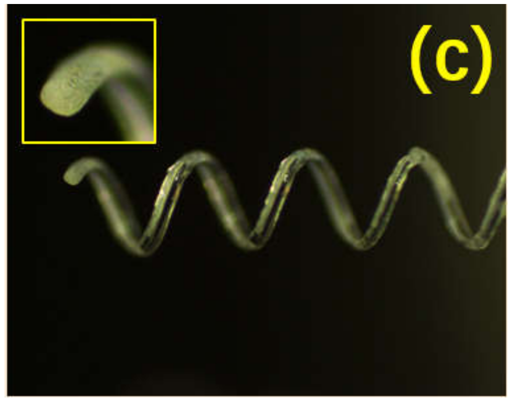
Feature size **VS** laser power



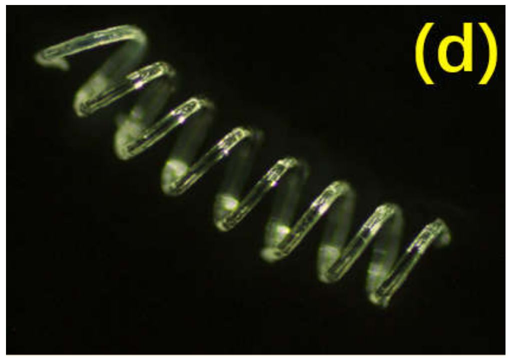
Coil fabricated in Z direction



3 mW

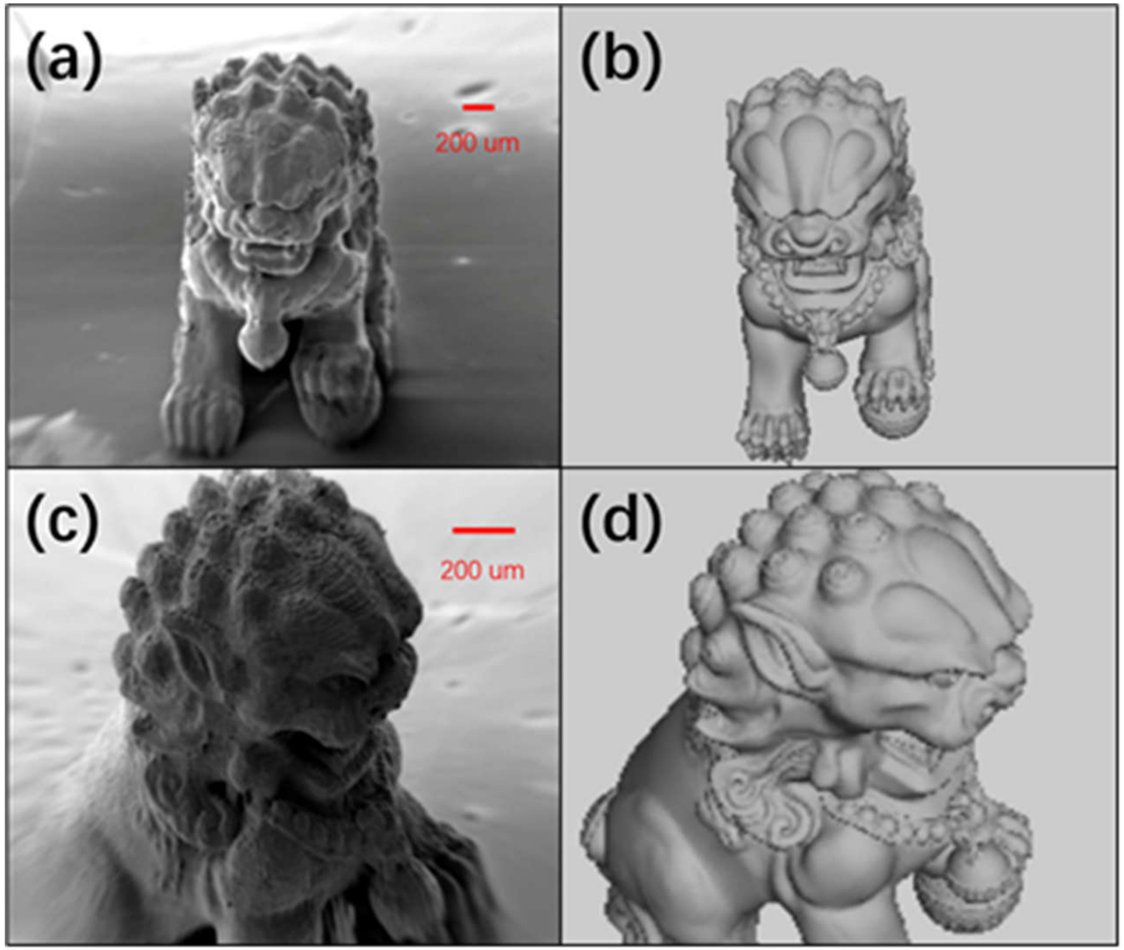


4 mW



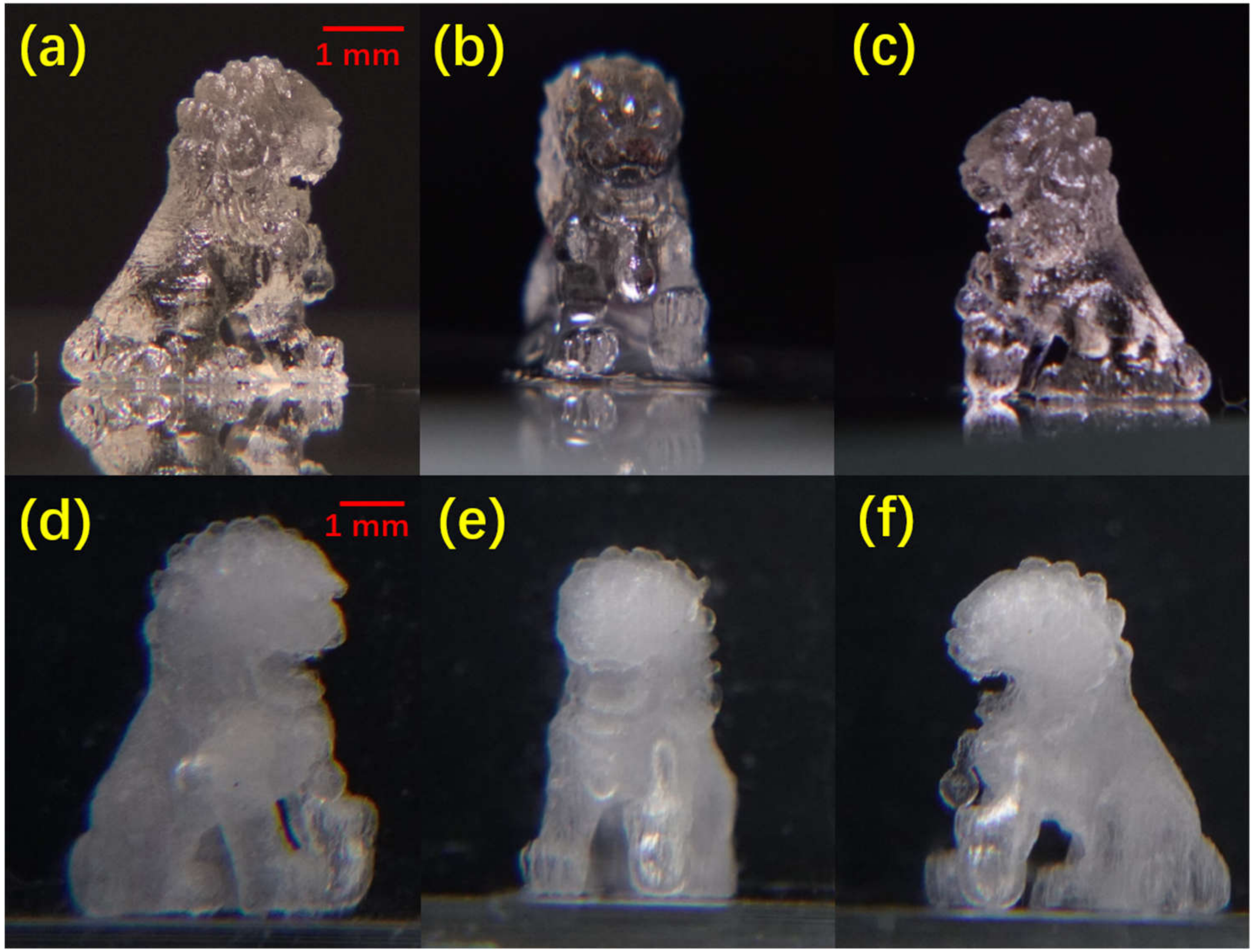
5 mW

Large scale 3D printing by SSTF-TPP – resolution ~10 μm



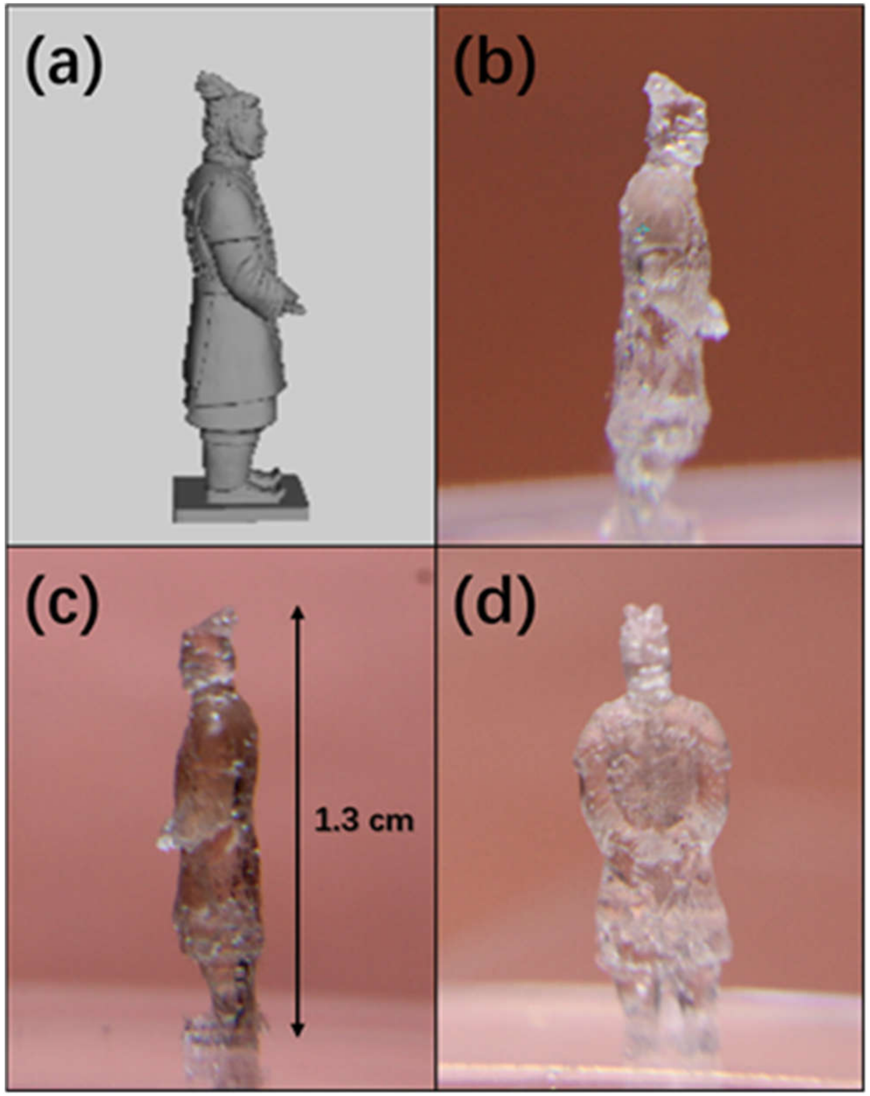
Chinese Guardian lion. Height: 2 mm; resolution: 10 micron

Large scale 3D printing by SSTF-TPP – resolution ~20 μm



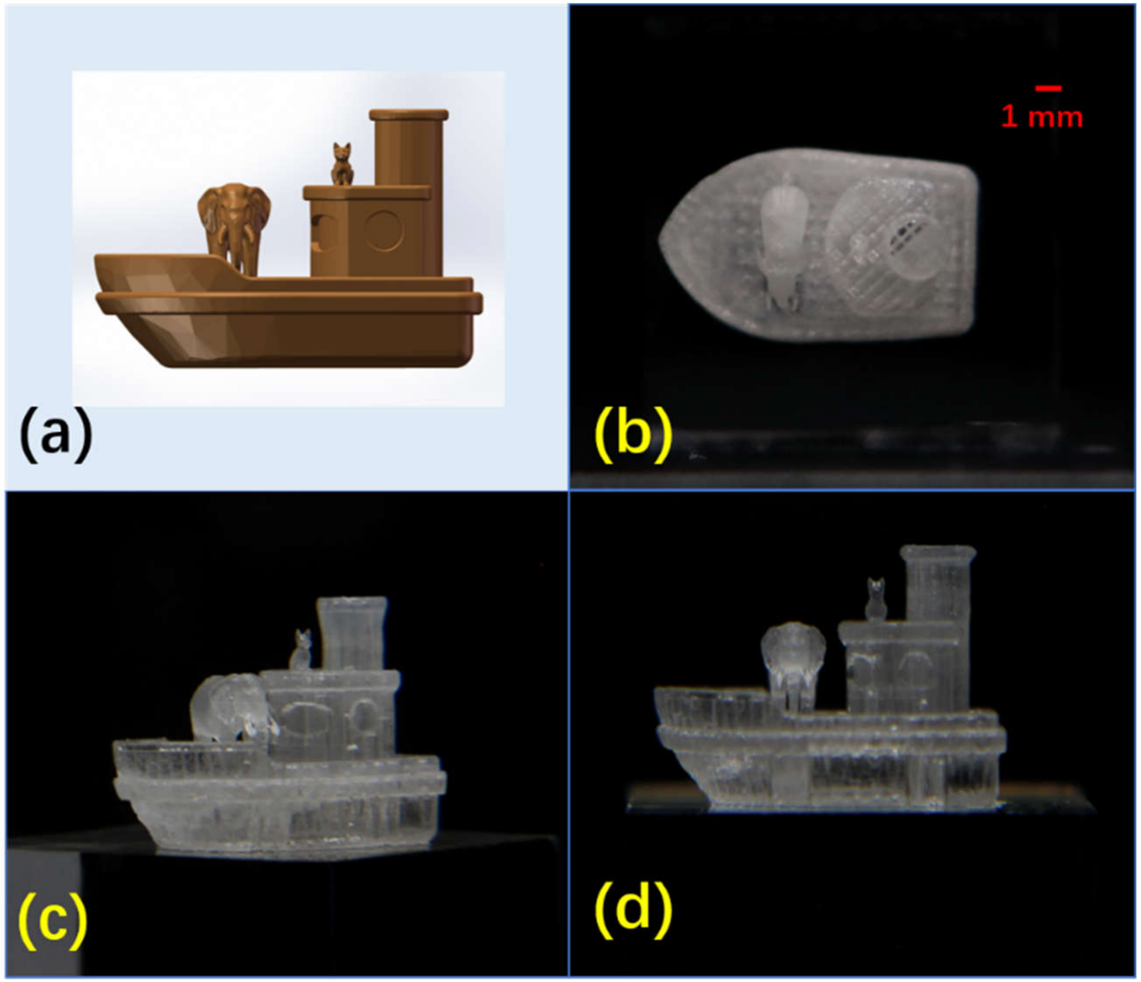
Chinese Guardian lions.
Height: 4 mm and 6 mm; resolution: 20 micron

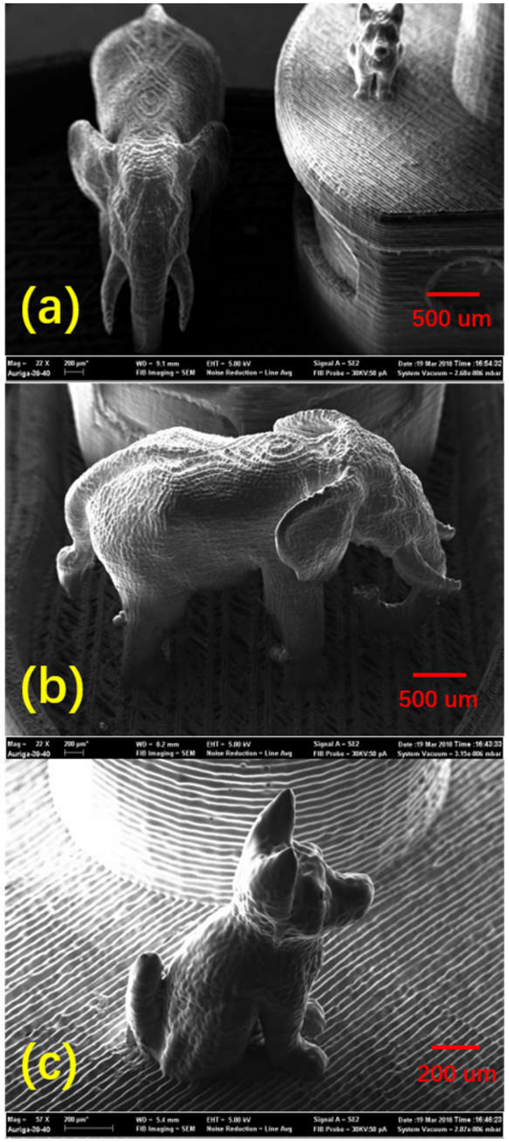
Large scale 3D printing – resolution ~40 μm



- Terra cotta warrior.
- Height: 13 mm;
- resolution: 40 μm

Rapid 3D printing with tunable resolution





Boat: 8-mm height, 40 um resolution

Elephant: 3 mm height, 20 um resolution

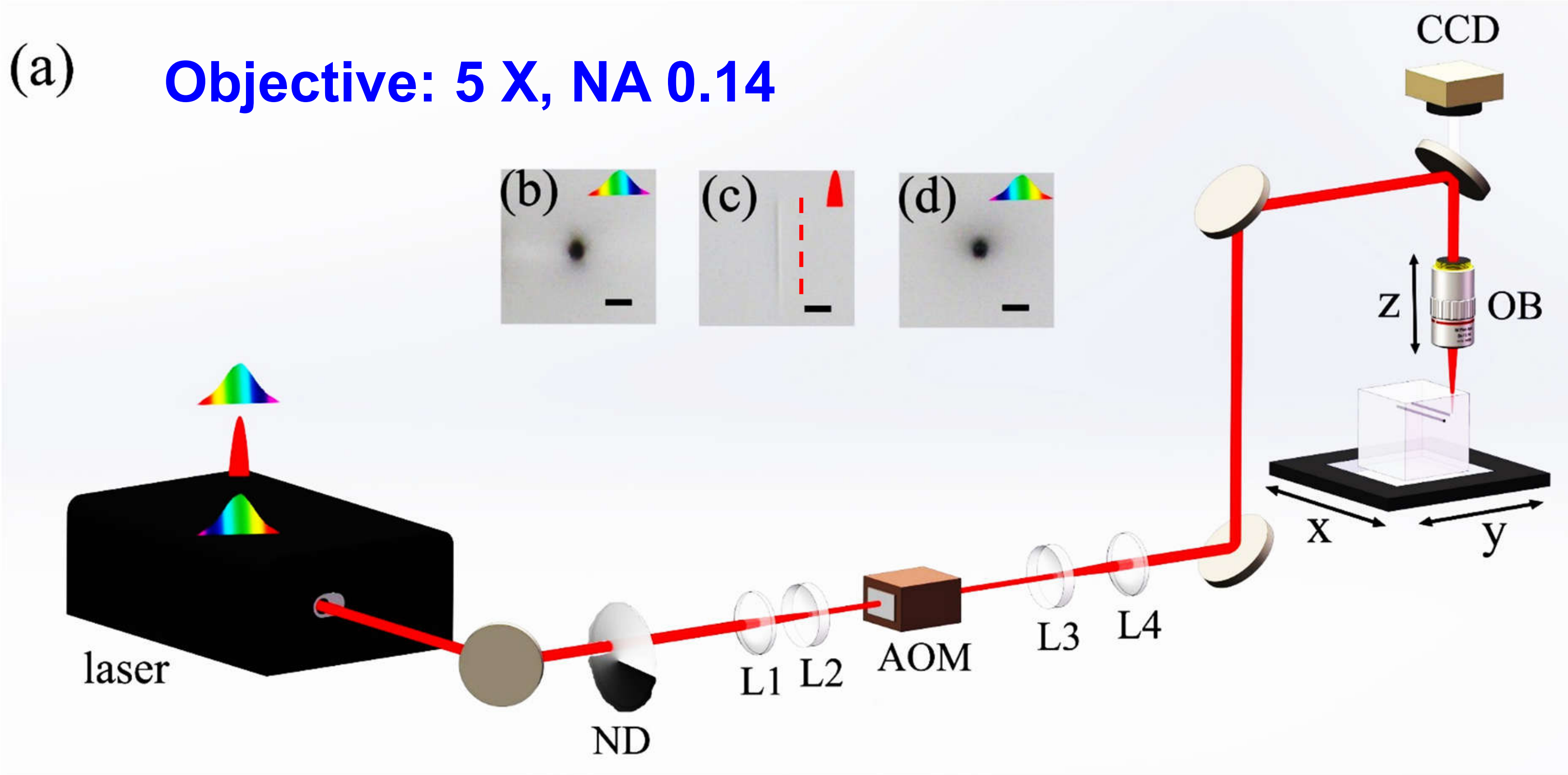
Dog: 1 mm height, 8 um resolution

Two connected stories:

1. **3D microprinting in polymer with heights above 1 cm;**

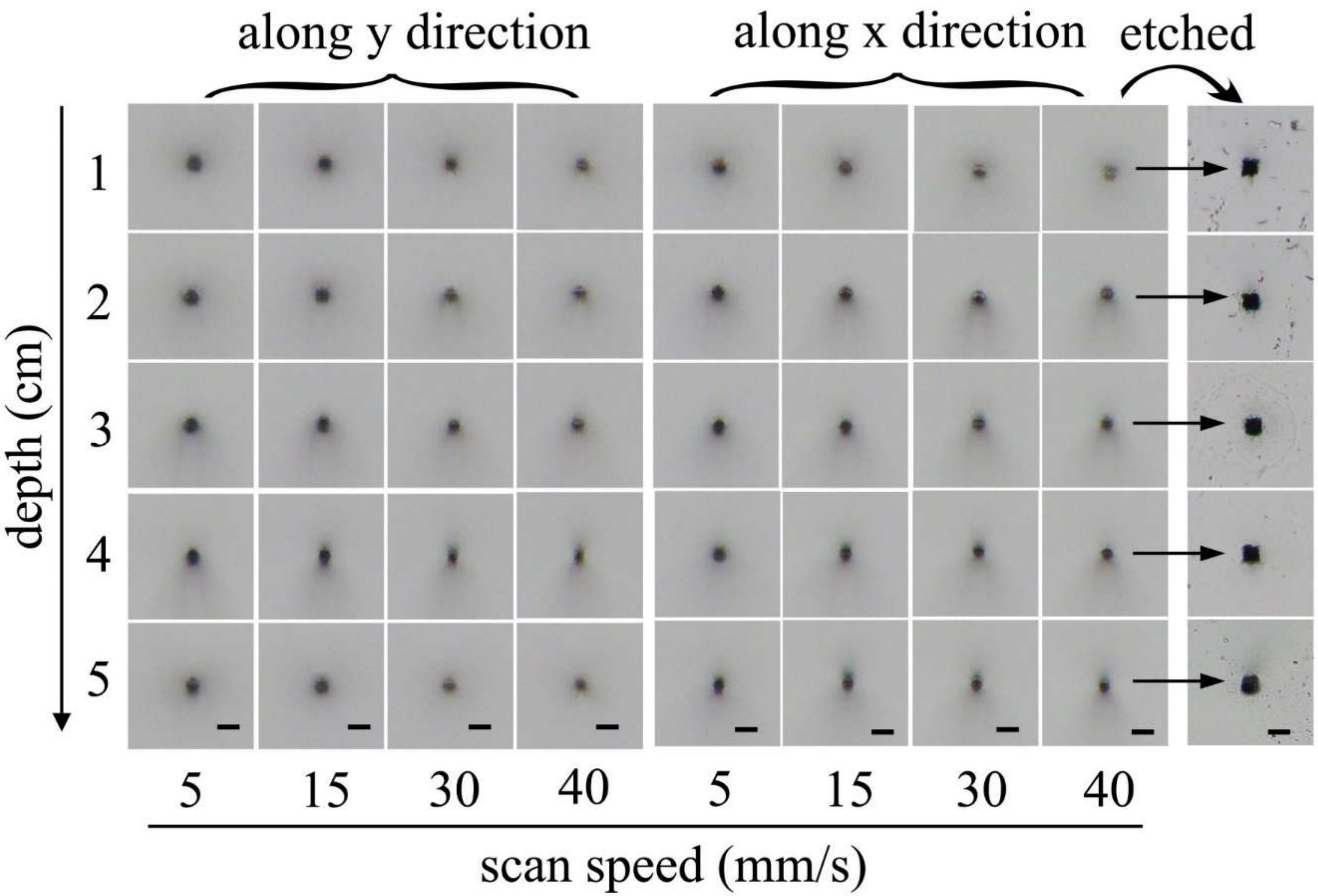
2. **3D microprinting in glass without optical aberration *(physics to be identified).***

Experimental setup and the major result



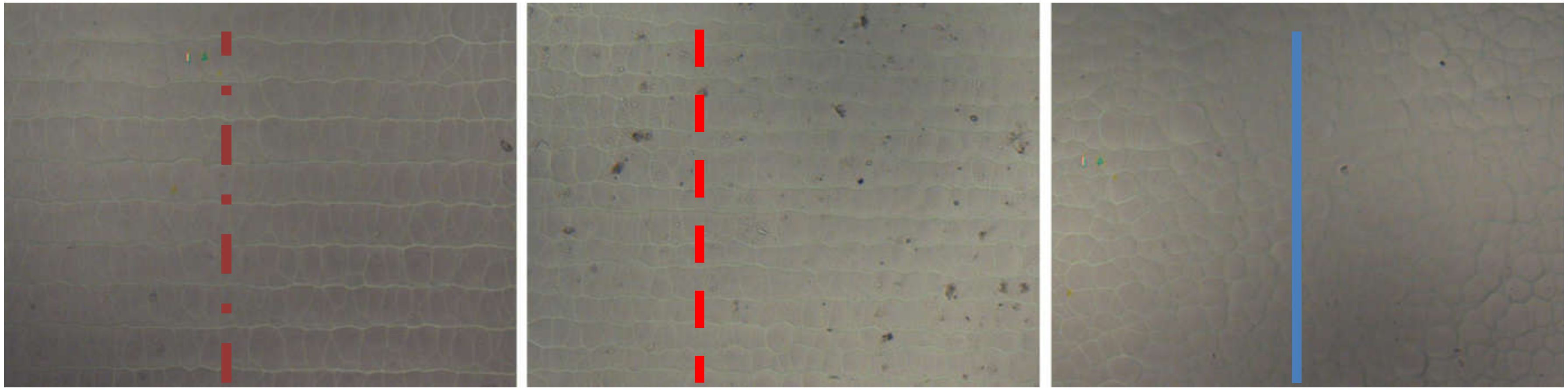
(a) Schematic of the experimental setup. Cross-sectional view of optical micrographs of lines written with (b) positively chirped 10 ps laser pulses, (c) 190 fs laser pulses and (d) negatively chirped 10 ps laser pulses. Scale bar, 25 μm. Laser repetition rate: 500 kHz.

Tiny modification areas independent of depth !

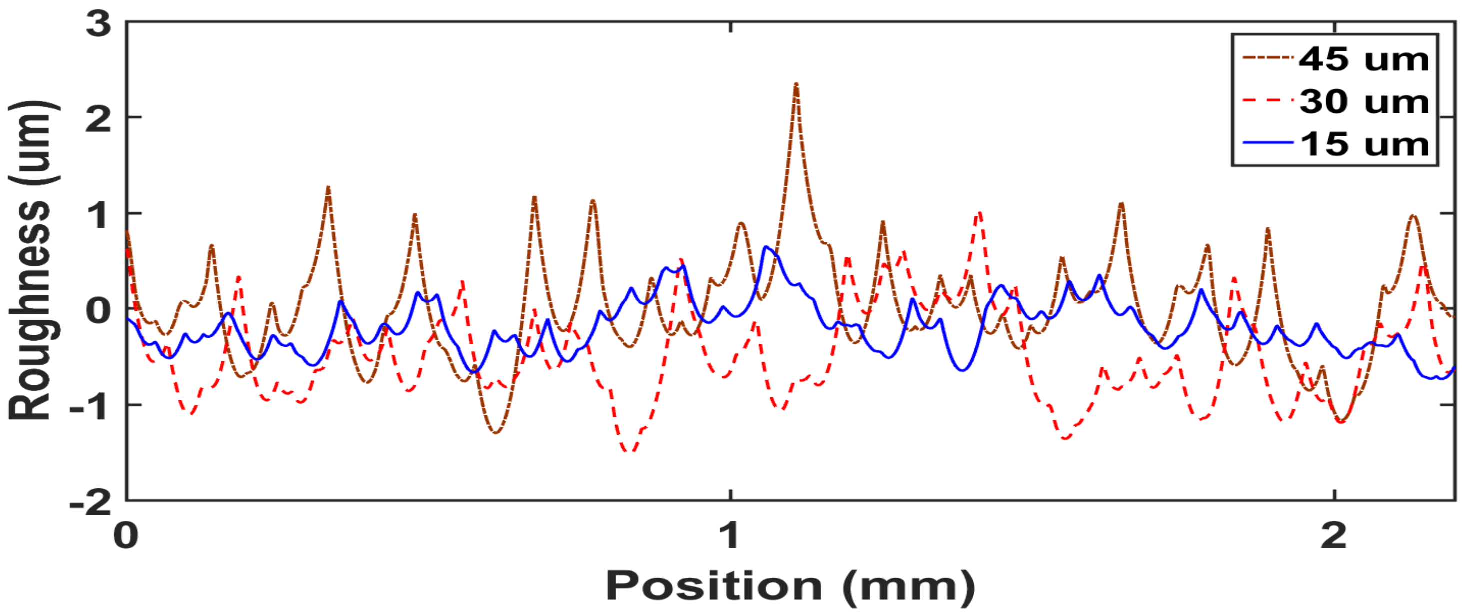


Cross-sectional view of optical micrographs of lines written by 10 ps laser pulses. (Patented)

Evidence showing a resolution of ~15 μm in Z direction



Layer spacing in Z direction: 50 μm ➡ 30 μm ➡ 15 μm



- So, we have the aberration free focusing, solving one of the key problems.
- But, one thing is still missing here:

- Remember, the chemical wet etching is dependent on the orientation of polarization of the writing beam. How can we remove such dependence to achieve homogeneous writing of complex 3D structures ?

Towards polarization independent internal write

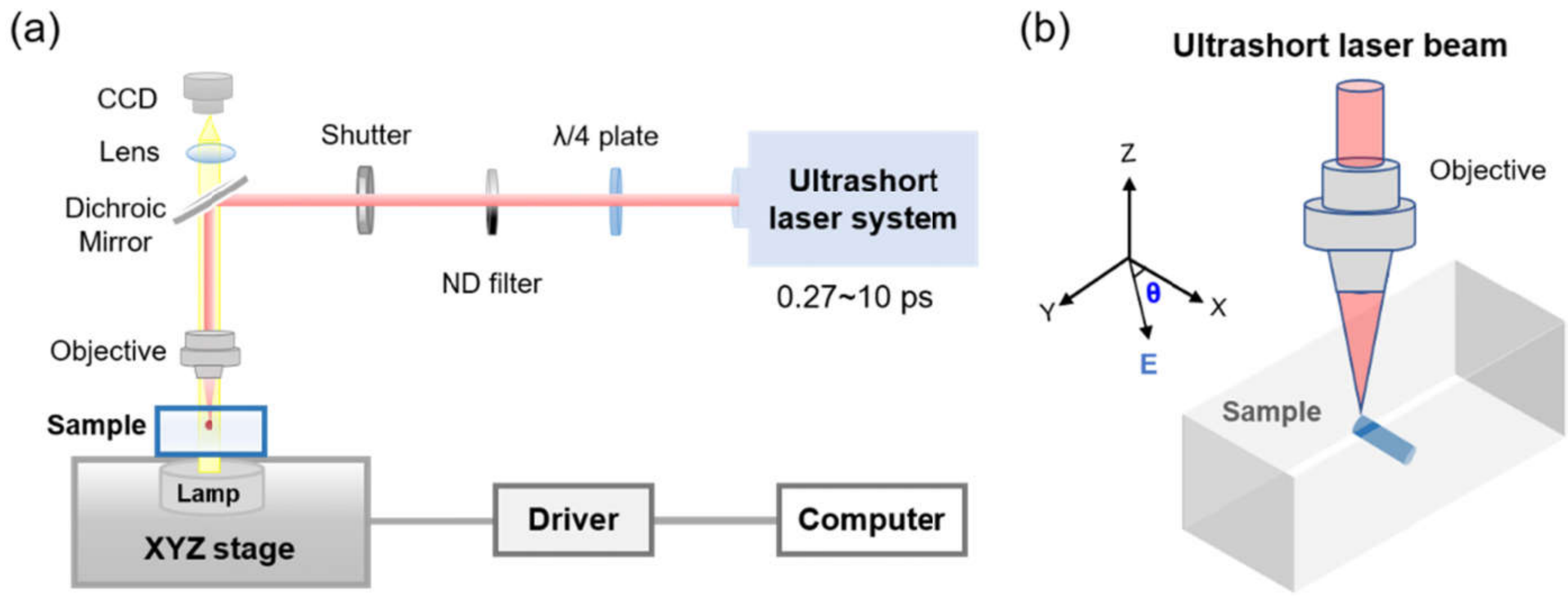


Fig. 1. Schematic of (a) the experimental setup for ultrashort laser processing and (b) laser direct writing in fused silica for modification.

Objective lens: NA 0.3

Polarization sensitivity vs. pulse duration

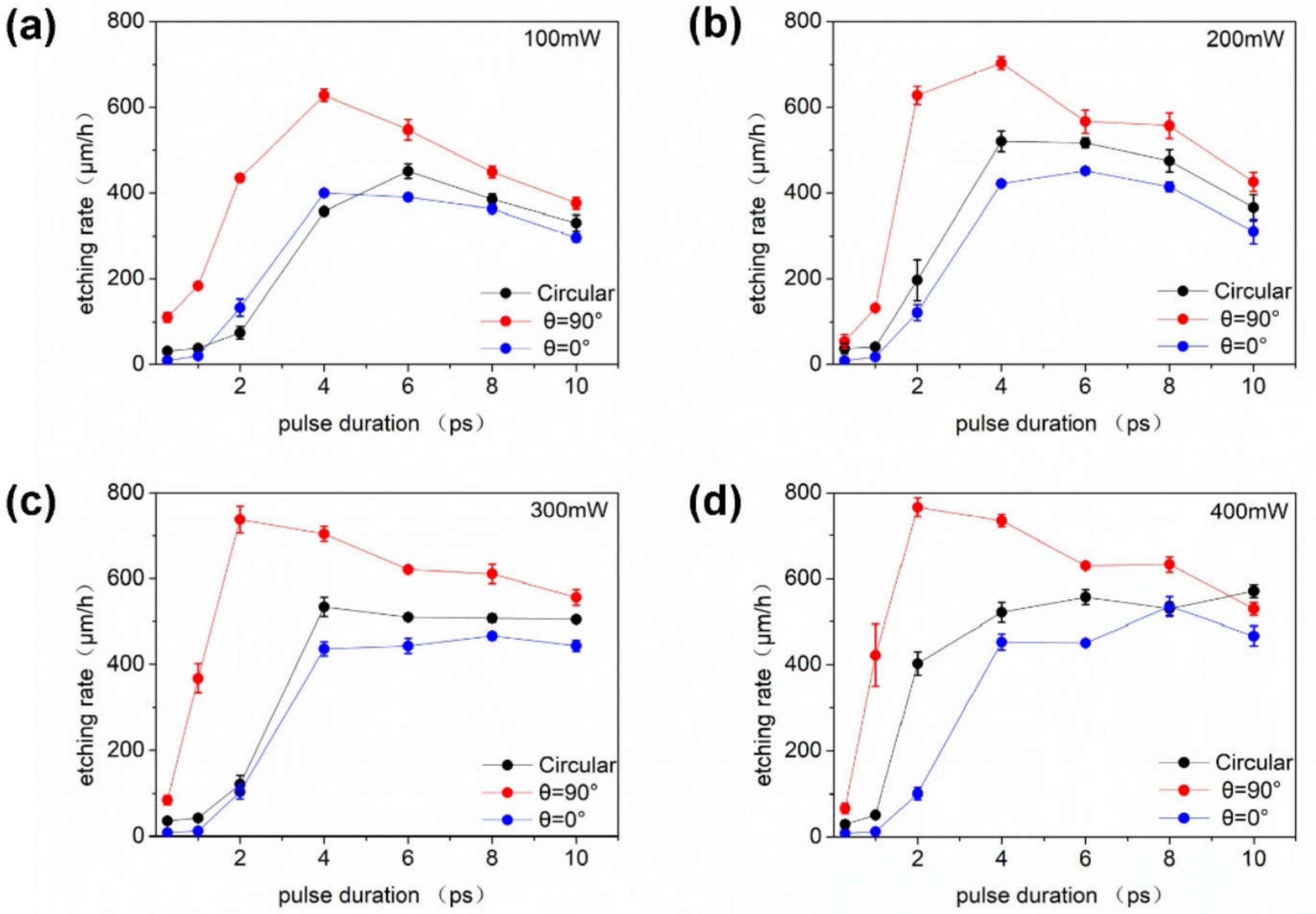
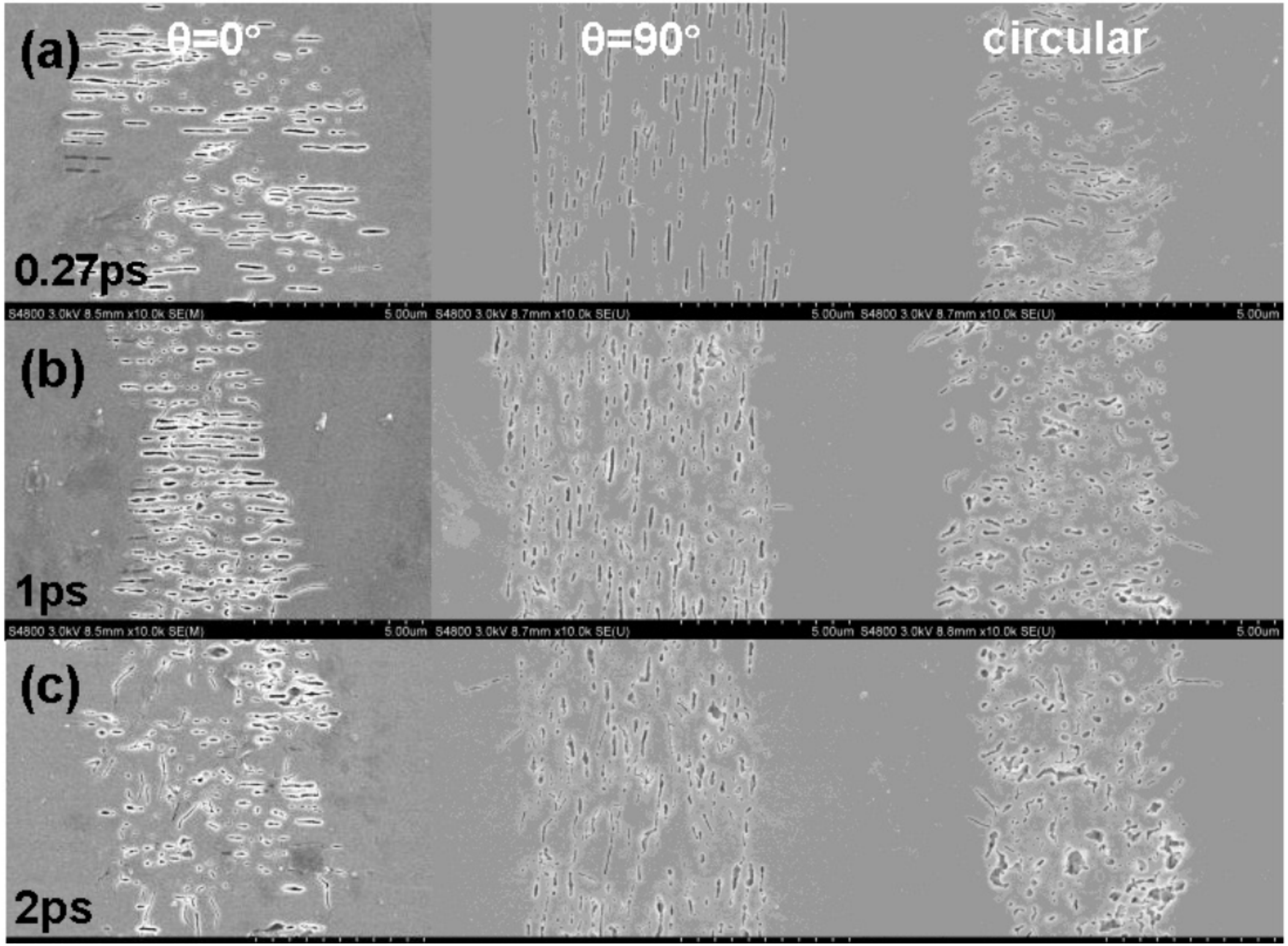
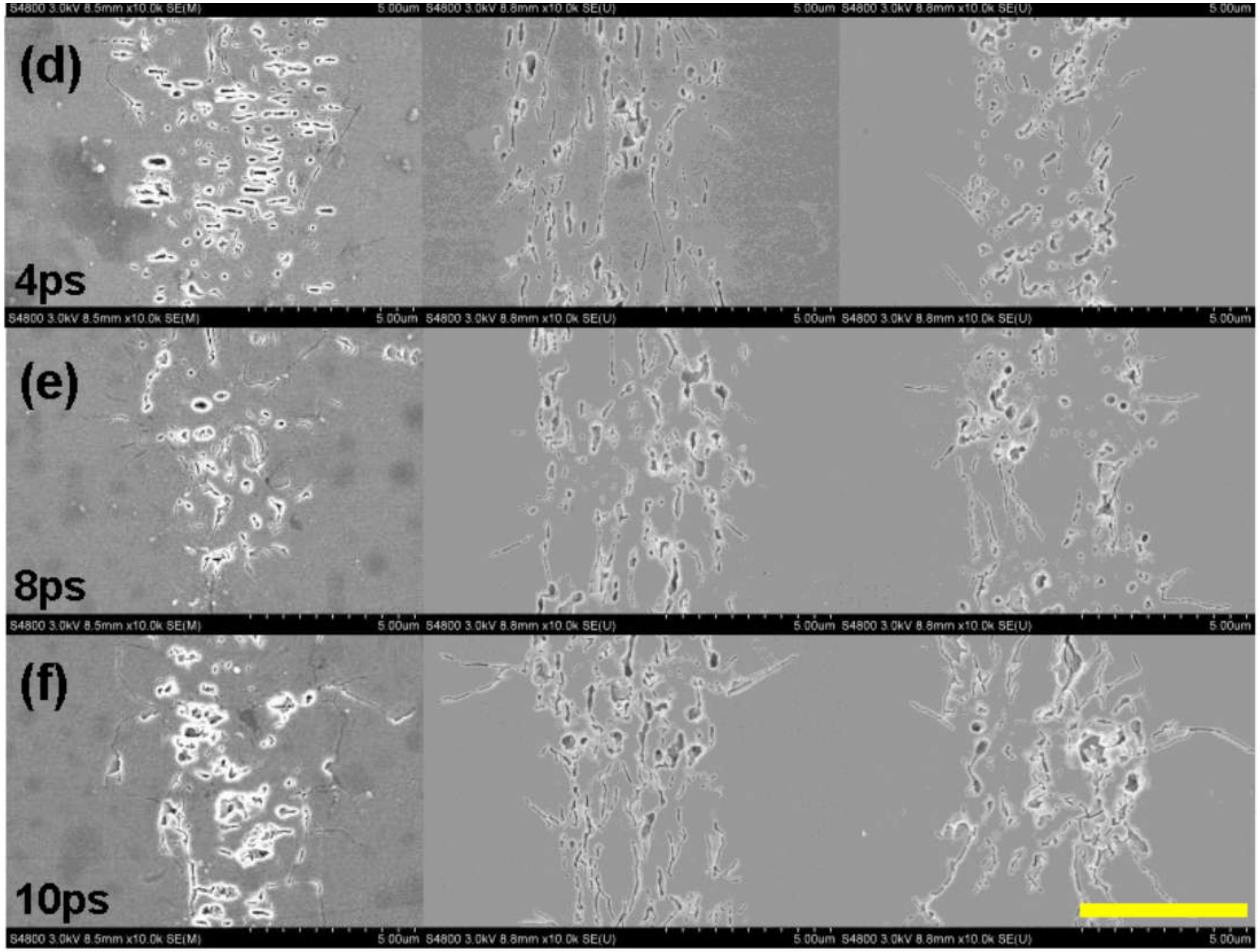


Fig. 2. Etching rates of laser modified lines in fused silica versus pulse durations at different polarization conditions and laser powers: (a) 100 mW; (b) 200 mW; (c) 300 mW; (d) 400 mW.

Shorter pulses: nanogratings

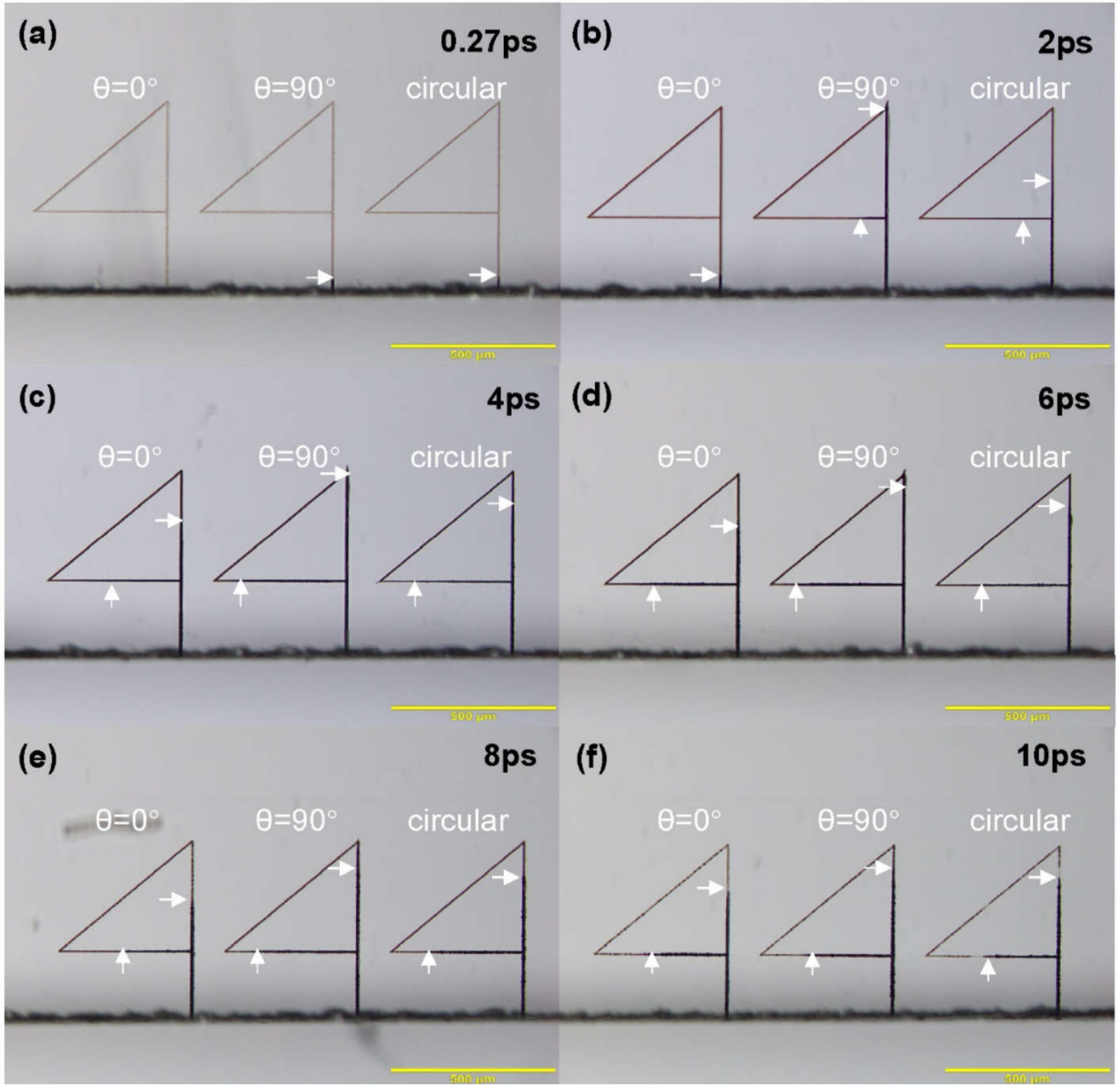


Longer pulses: stress induced cracks along scan direction



Scale bar: 5 μm

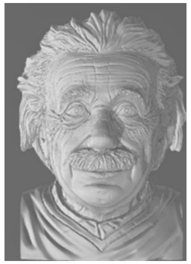
Selective etching independent of polarization

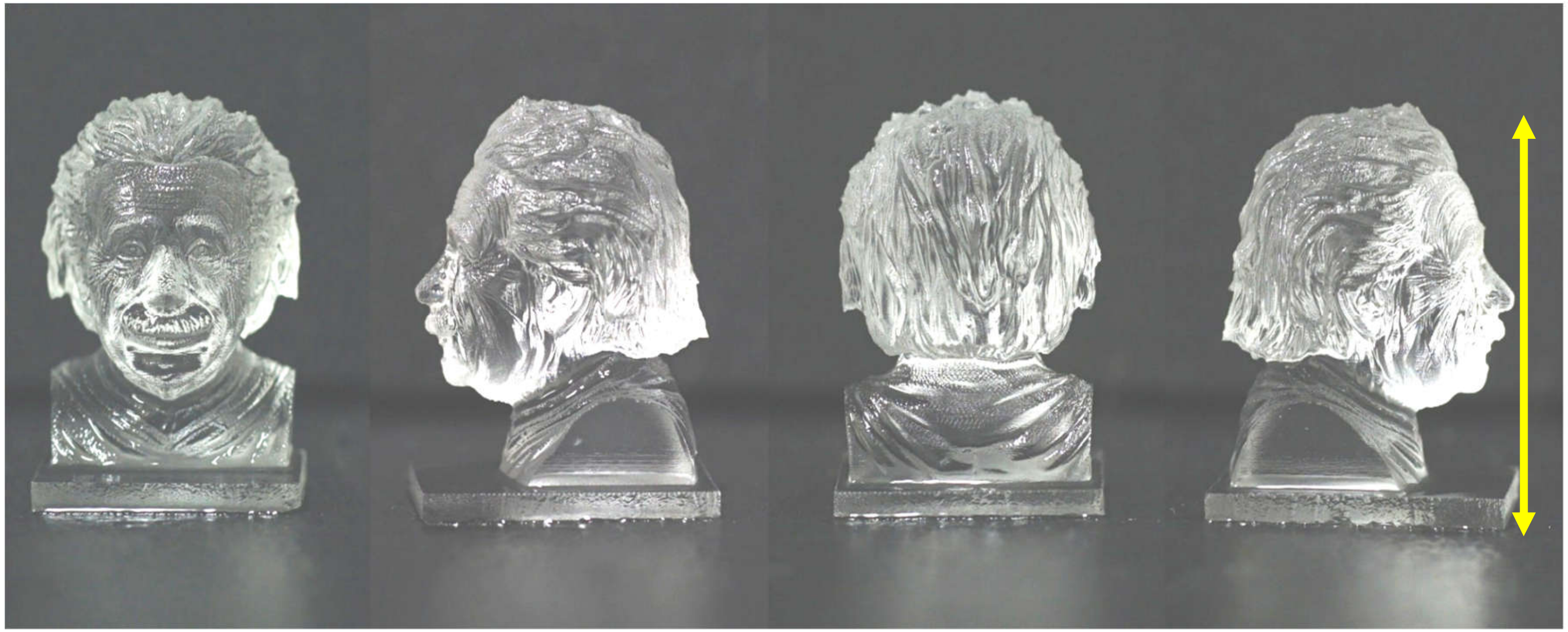


Picosecond laser:
one stone two birds

With the picosecond laser pulses, the difficulties in maintaining the high resolution at various depths and a polarization insensitive internal modification can be overcome at once!

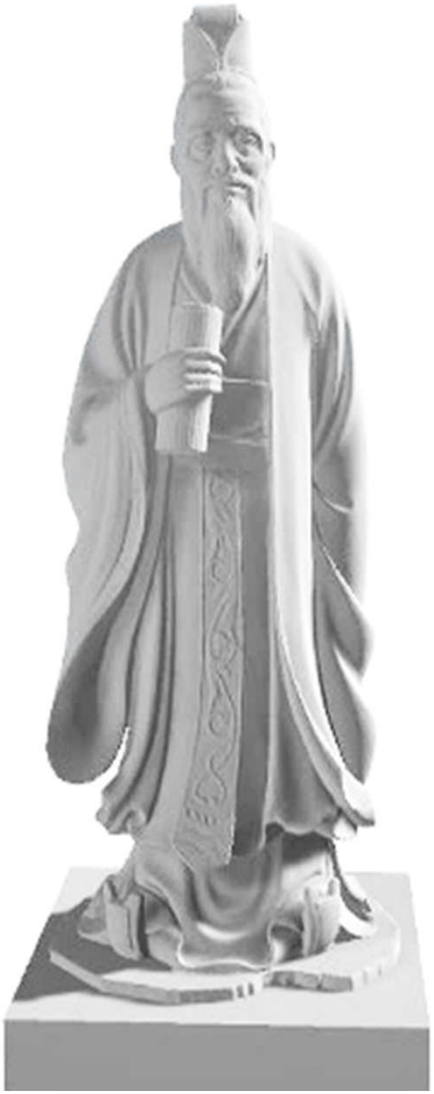
Example: Einstein of a height of 2 cm

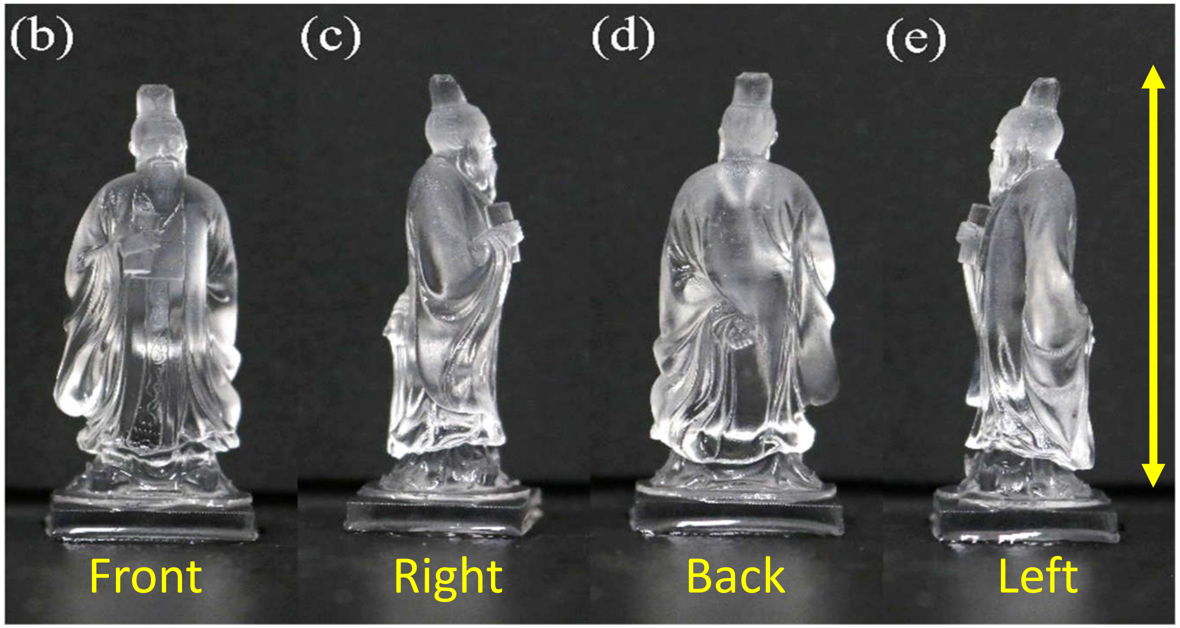




~ 2 cm

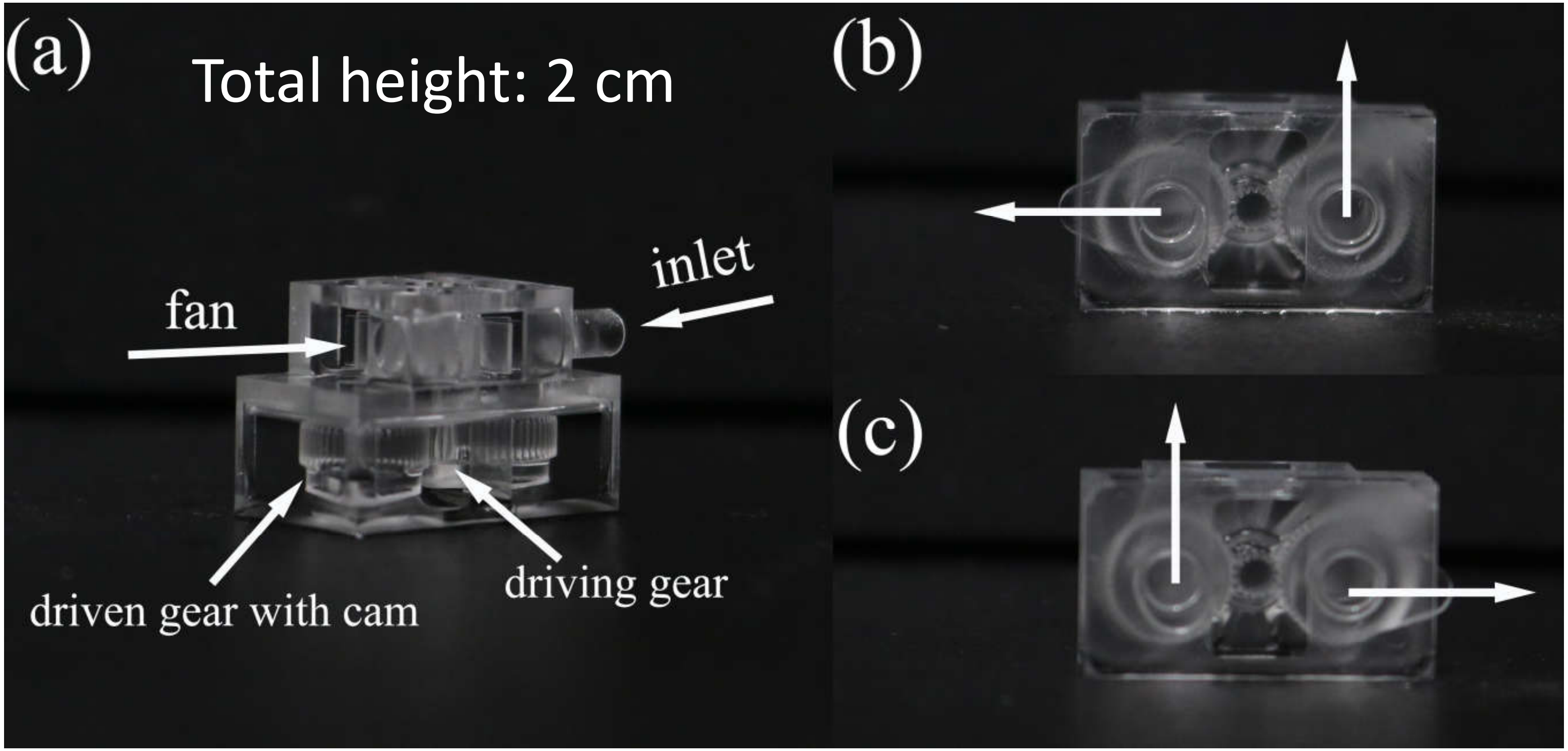
Example: Confucius of a height of 3.8 cm





3.8 cm

Example: a micromachine with movable parts



Two fans (upper floor) which can be driven to rotate with three driving gears (lower floor)

Conclusions

- SSTF is very useful for large-height 3D printing in polymer with high resolutions, where low-order nonlinearity plays the key role.

- Amazingly, picosecond laser writing gives rise to aberration-free and polarization-independent internal processing in glass !

- Future: understanding new physics and exploring new applications with new characteristics enabled by loosely focused picosecond laser !

Thank you !