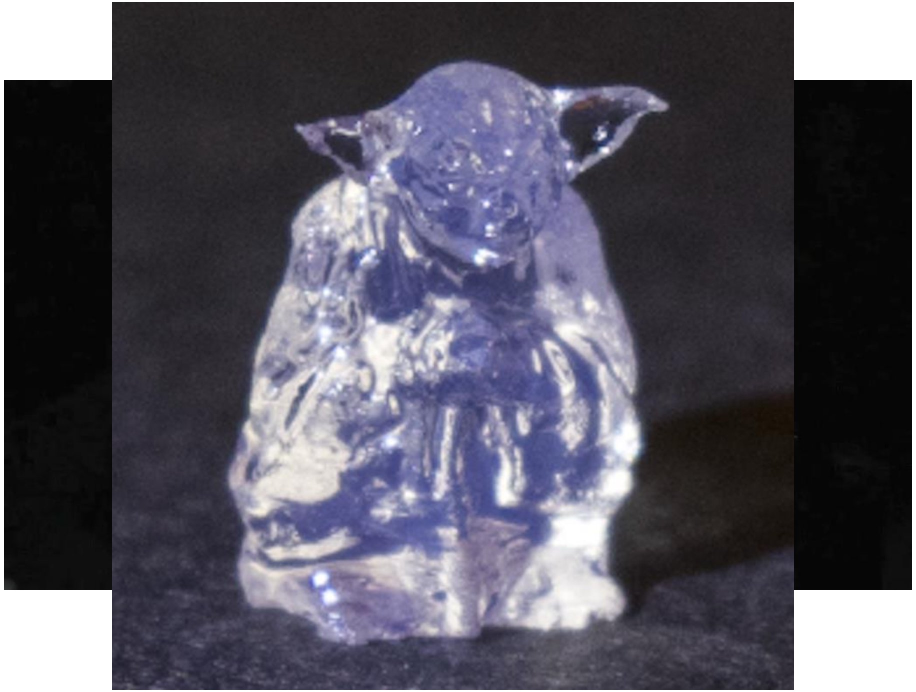
Modules of the 2025 course

Topics covered	No	Lecture/Date
VAT Photo polymerization (history) – DLP printer – light engine – part I	5	20.03.2025
DLP printer – chemical components in a photoresin – role of oxygen – CLIP method– part II	6	27.03.2025
Tomographic Volumetric Additive Manufacturing (TVAM): principles and applications	7	03.04.2025
Two photon Polymerization : nanoscale printing	8	10.04.2025
Two photon Polymerization : applications	9	17.04.2025
EASTER BREAK		22.04.2025
Prof. Paul Dalton, University of Oregon: Met Electro Writing (nanoscale)	10	1.05.2025
Gari Arutinov, Holst Center for AM: Mass transfer of microcomponents	11	08.05.2025
Julian Schneider: Scrona	12	15.05.2025
Patrizia Richner: Sonova (hearing aids). // **Design Competition**	13	22.05.2025

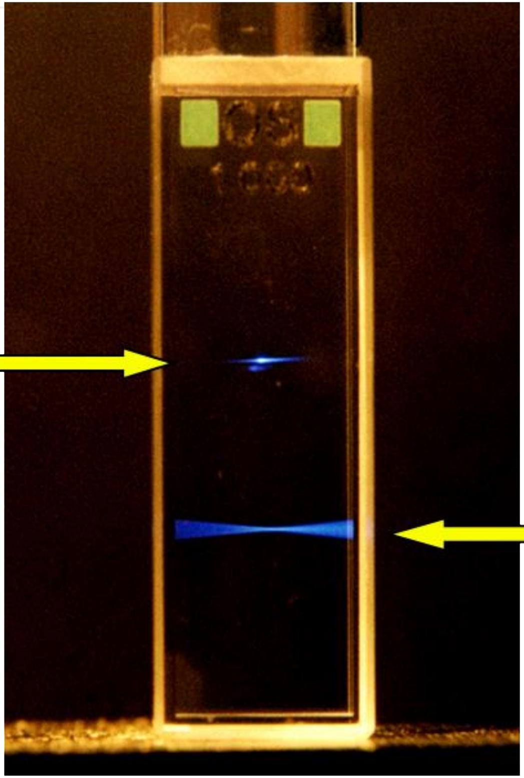
QUIZZ #2

2 Photon printing



Recap: Two-photon absorption

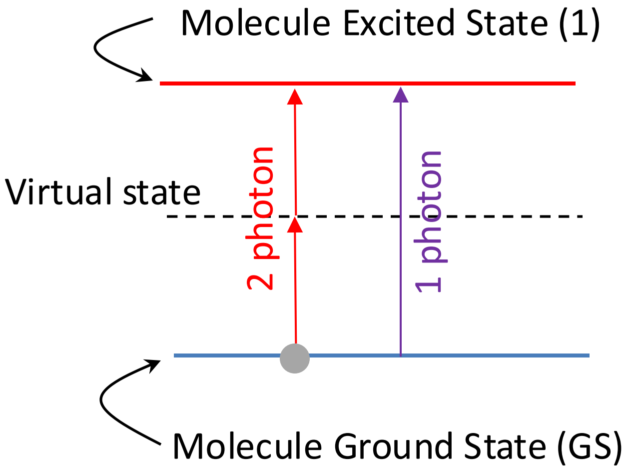
Excitation by two photons is confined to a volume very close to focus where intensity is highest , giving rise to *pinpoint 3D resolution*



Excitation by one photon results in absorption along the entire path of the laser beam in the cuvette.

Two-photon absorption

<u>Example:</u> 2 photons infrared of wavelength $\lambda_1 = 800\,nm$ ( ) have a combined energy of and can produce absorption at ( )



In terms of absorption for the light intensity

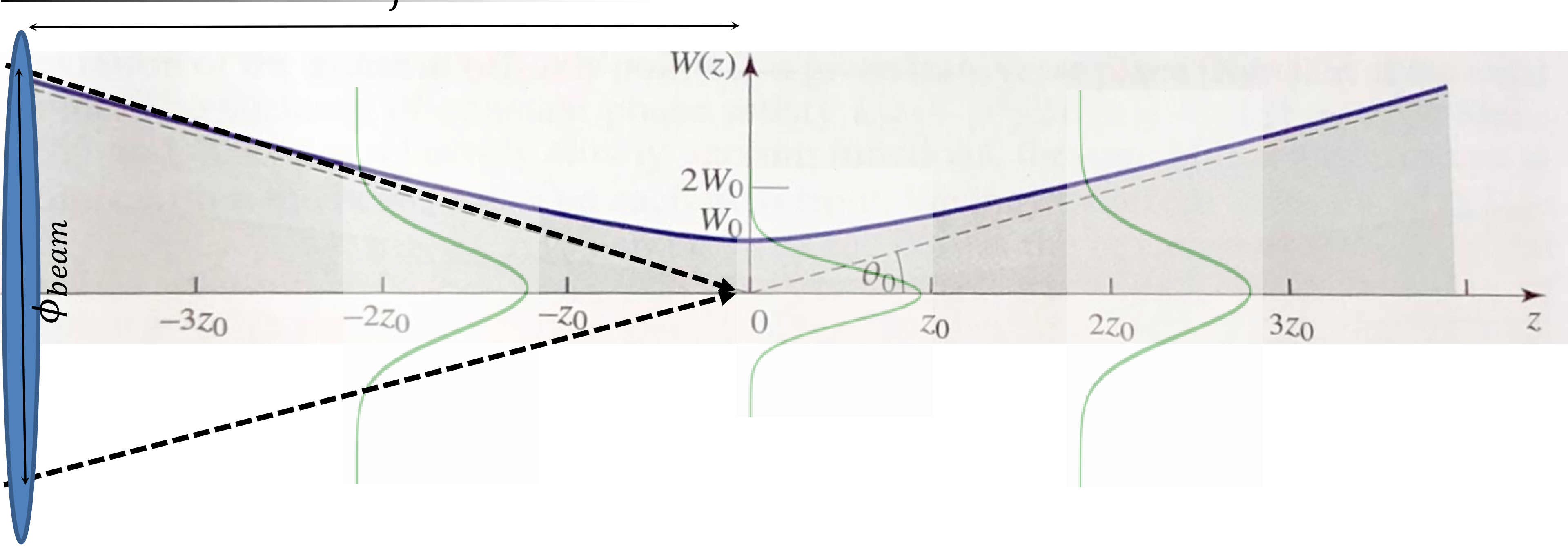
Single photon

Two photon

Estimation of the light intensity required to have a two-photon absorption of similar magnitude to single photon absorption:

Typ. Values

Recap: Two-photon absorption



Two-photon absorption

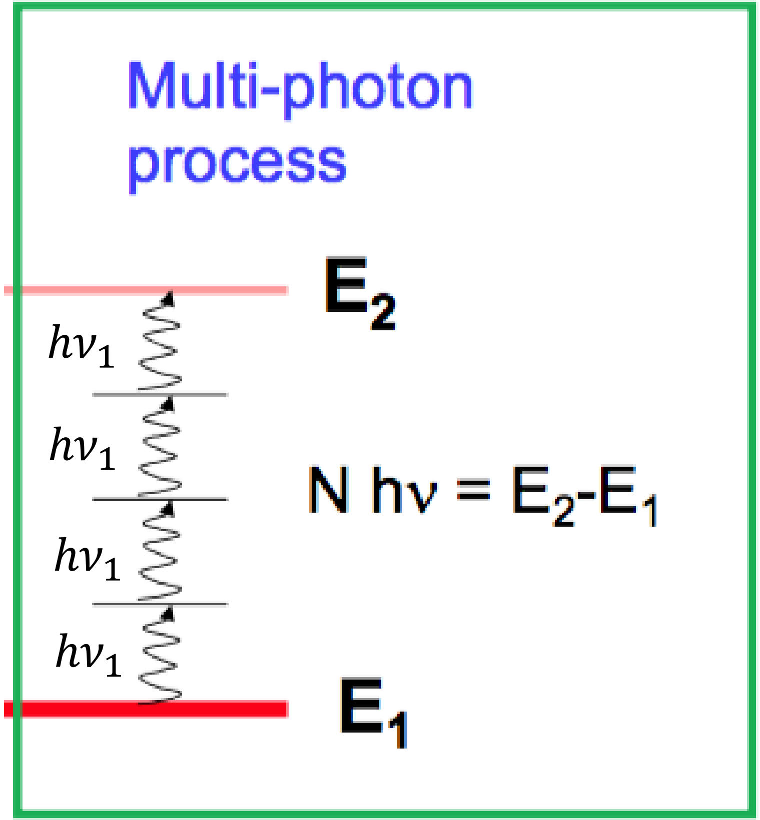
How to generate a laser power of 860 kW ?

Ans: pulsed laser

Multi-photon absorption

A material is transparent at a wavelength of λ_1 (i.e frequency) but can become absorptive at very high optical peak powers

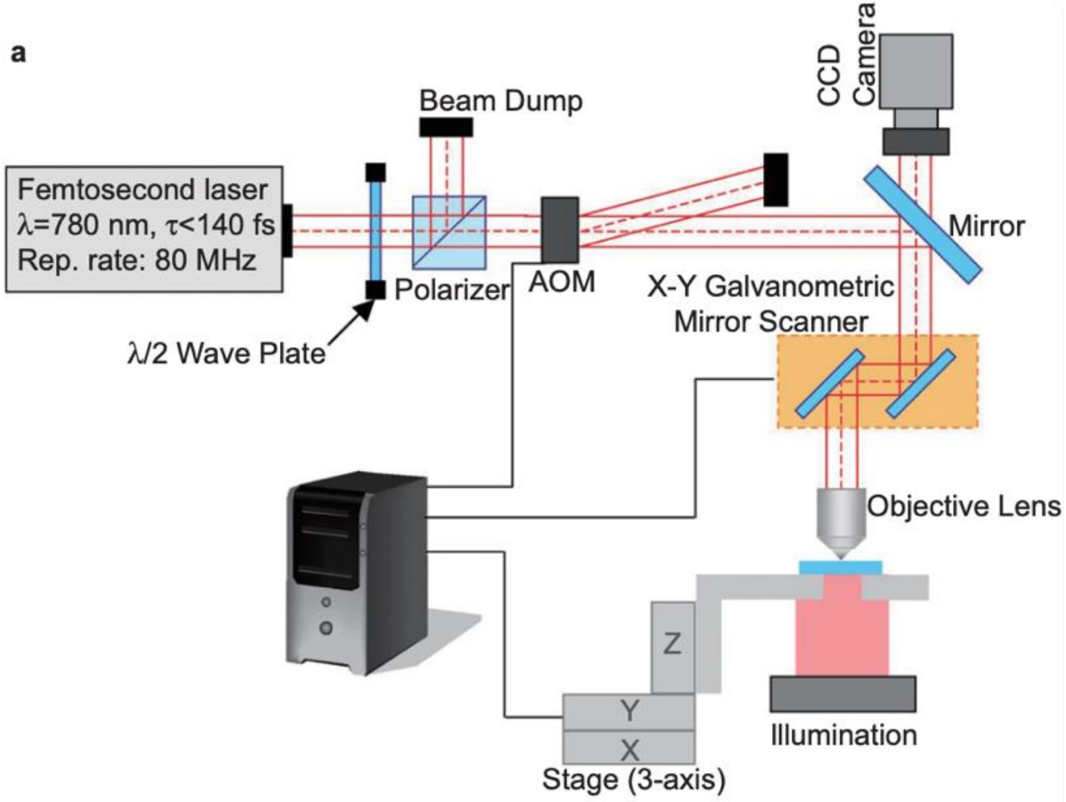
When N=2, the process is called Two photon absorption (TPA)



Two-photon absorption

		τ	$P_{average}$	$1/T$	
FemtoFiber smart 780	785 ± 5 nm	< 100 fs (typ. 80 fs)	> 120 mW (typ. 140 mW)	80 MHz	16

Typical setup for 2-photon polymerization



Original first demonstration

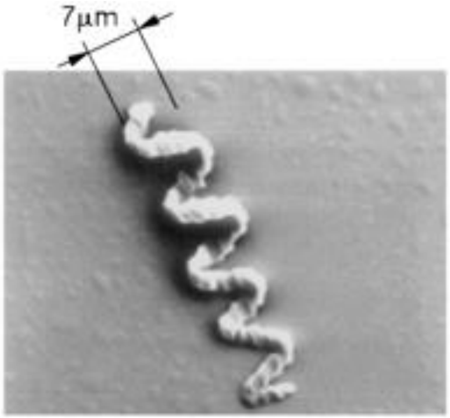
OPTICS LETTERS / Vol. 22, No. 2 / January 15, 1997

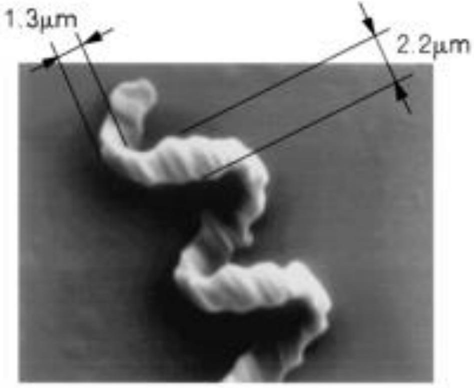
Three-dimensional microfabrication with two-photon-absorbed photopolymerization

Shoji Maruo, Osamu Nakamura, and Satoshi Kawata

Department of Applied Physics, Osaka University, Suita, Osaka 565, Japan

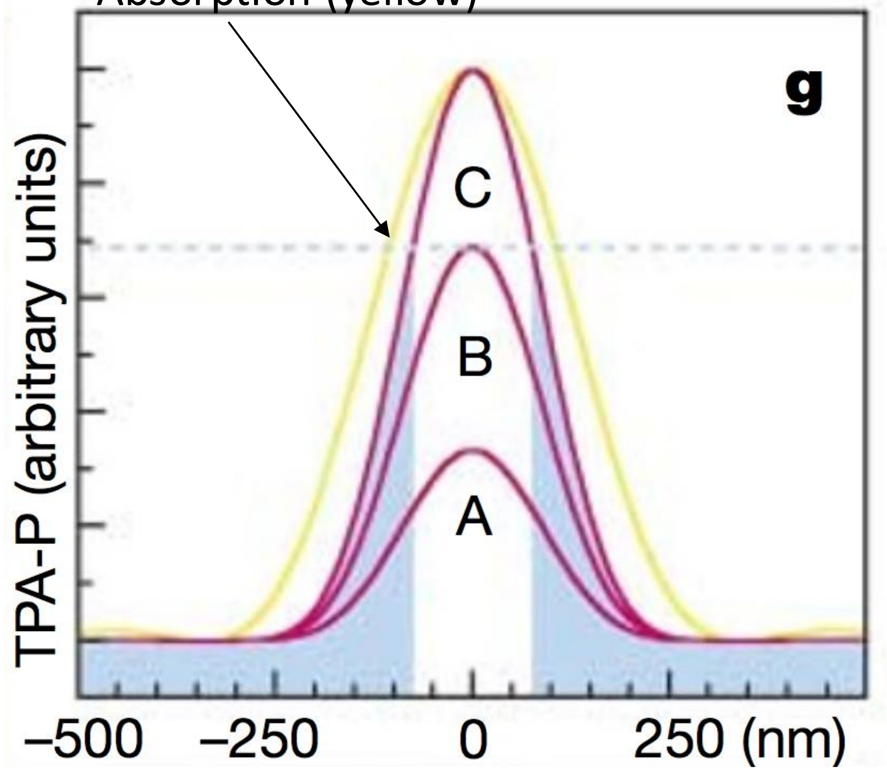
method. The light source that we used for the two photon absorption was a mode-locked Ti:sapphire laser whose oscillating wavelength, pulse width, repetition rate, and peak power were 790 nm, 200 fs, 76 MHz and 50 kW, respectively. The Ti:sapphire laser was excited by an Ar-ion laser of 8-W average power. The beam of the laser was focused into the resin with an objective lens whose N.A. was 0.85. A stage support



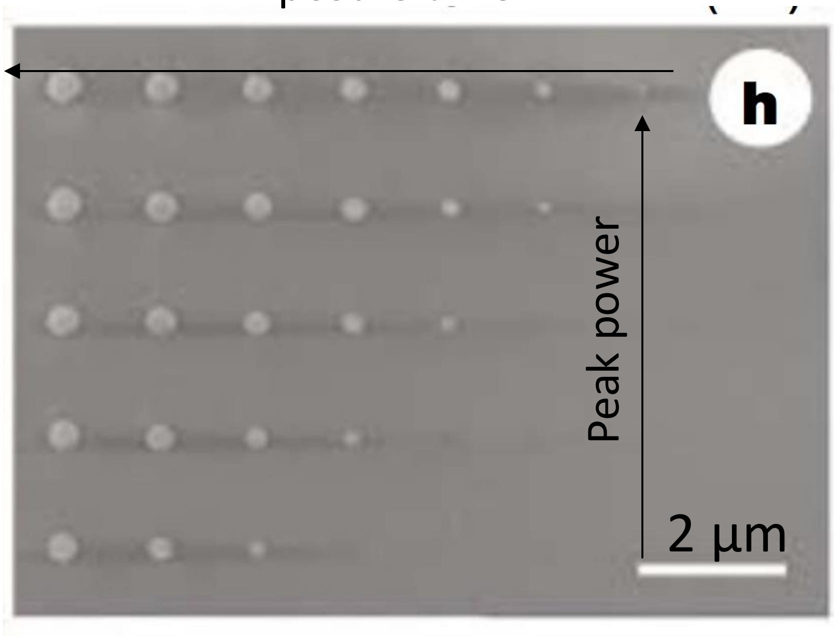


Printed voxel size

Single photon
Absorption (yellow)



Exposure time



Printed voxel size

Energy per pulse: E_{pulse} =137 pJ
Pulse duration: τ =150 fs

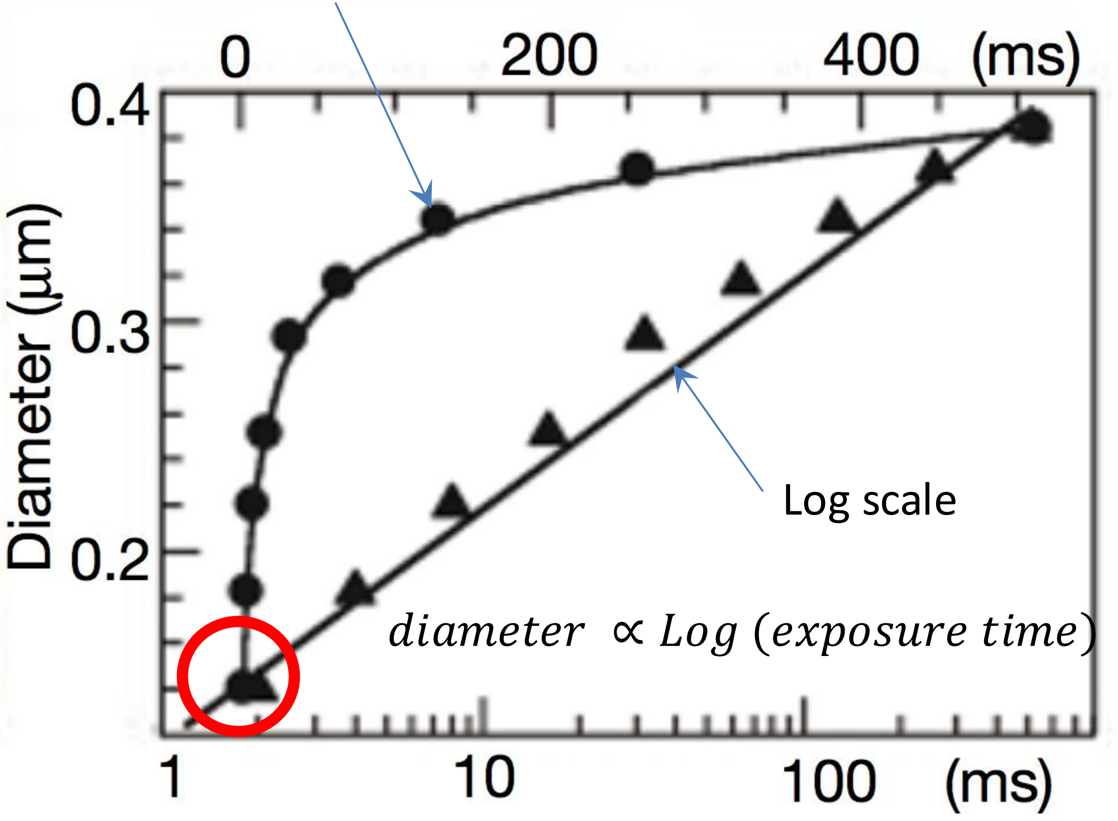
$P_{peak} =$

Numerical aperture NA=1.4

$waist =$

$I = \quad = \quad GW/mm^2$

Linear scale

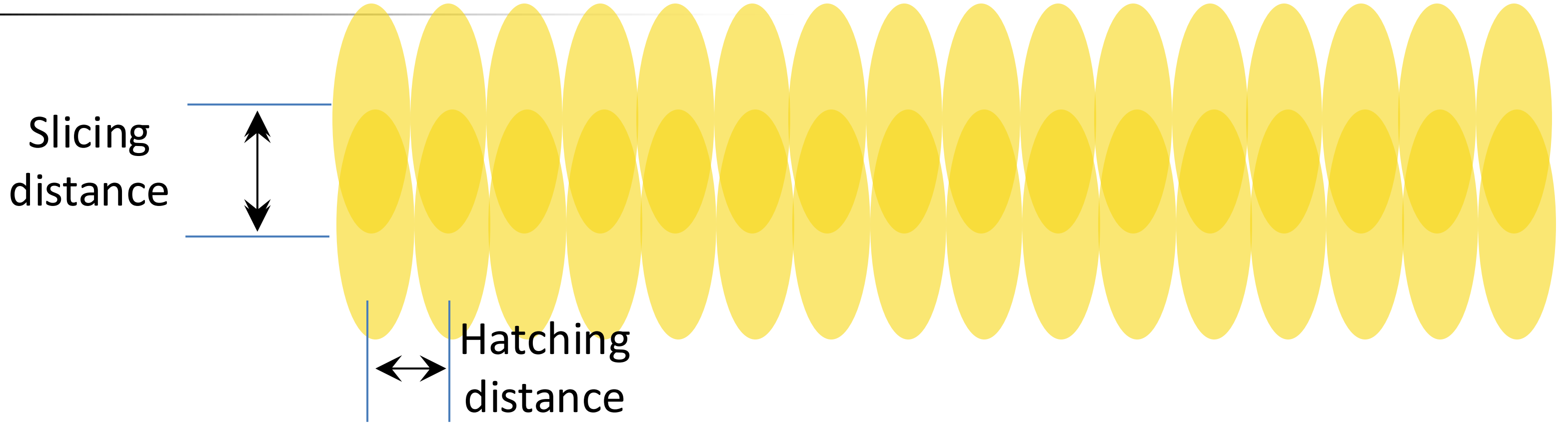


Log scale

$diameter \propto Log\,(exposure\ time)$

Exposure time

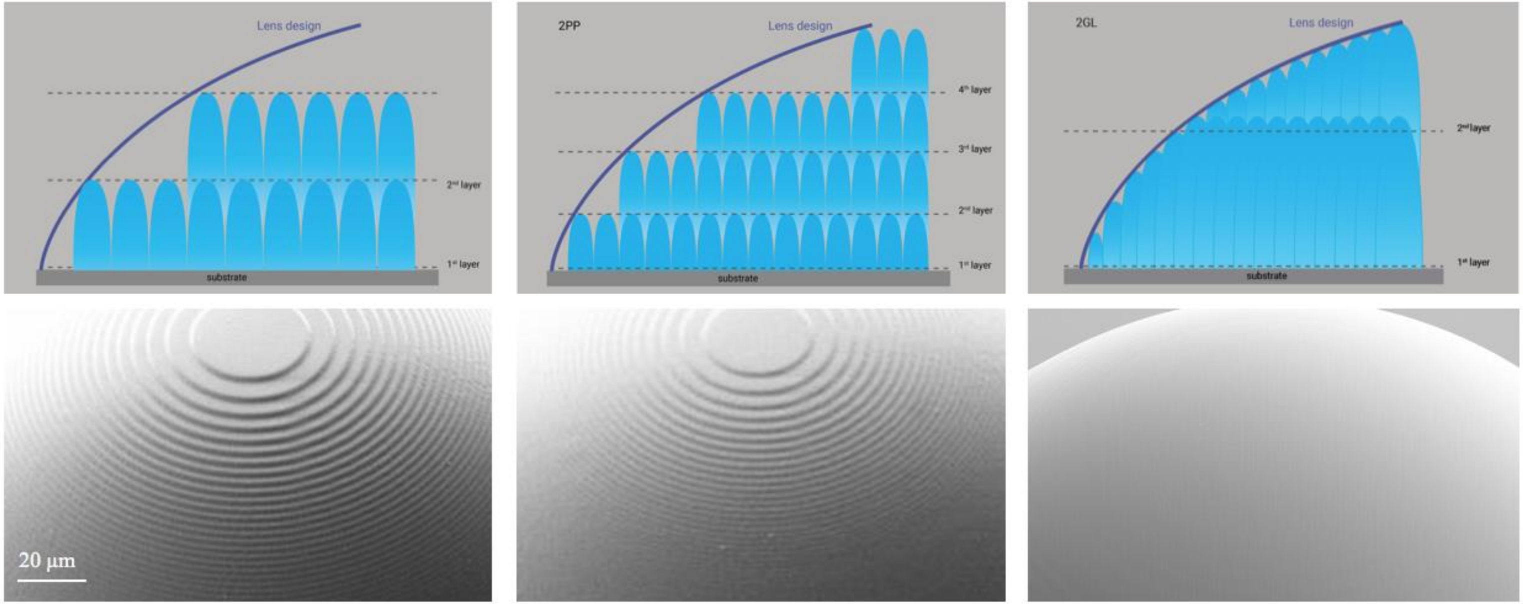
Fabrication time depends also on the scanning step



Scanning steps can be smaller to make a smooth surface

Challenge in high-precision 3D printing

Staircasing vs. printing speed



2PP with coarse slicing — 2PP with fine slicing — 2GL® with coarse slicing

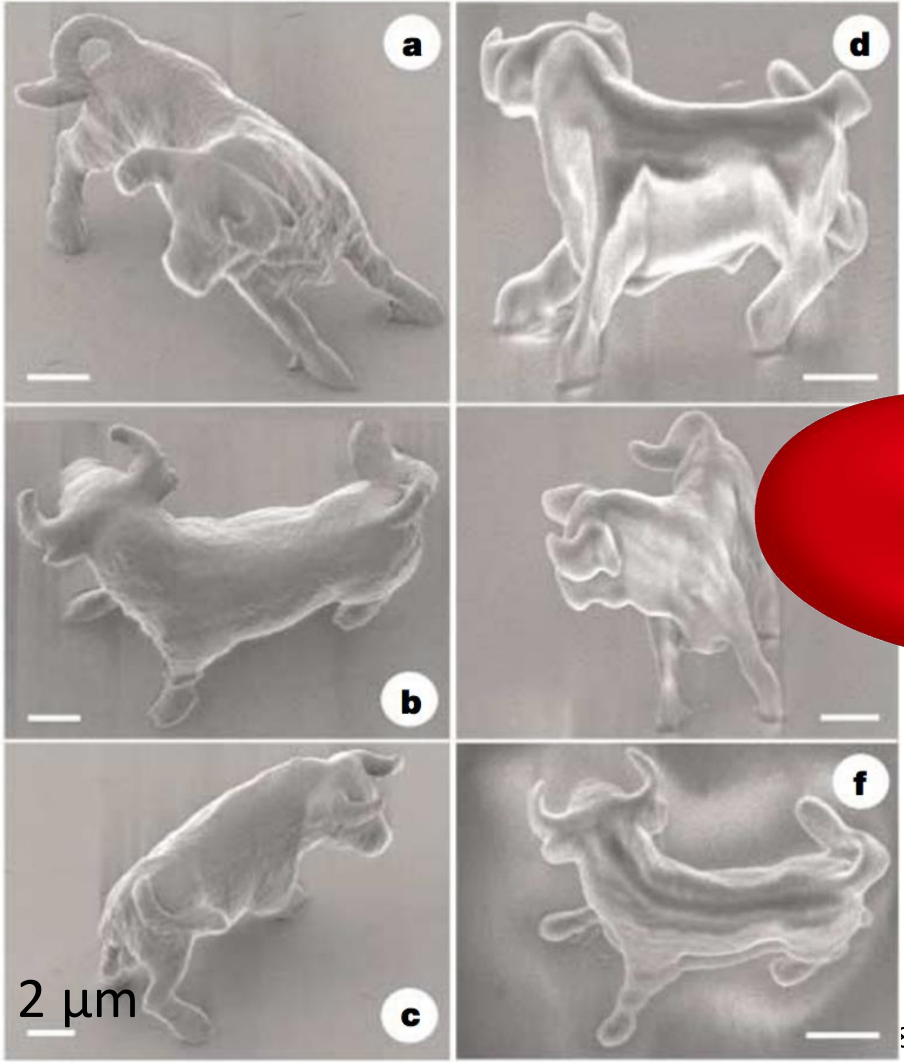
Courtesy of NanoScribe

Example:
20 x 20 x 20 um

2 ms exposure
Hatching-slicing (x,y,z): 0.15 um.

$\#points =$

$Exposure\ time =$



A red blood Cell for comparison

NATURE | VOL 412 | 16 AUGUST 2001

Although the wavelength is 780nm,
It is possible to make structures
With size 65 nm !!

By adjusting the dose i.e

$$Intensity \ * exposure \ times$$

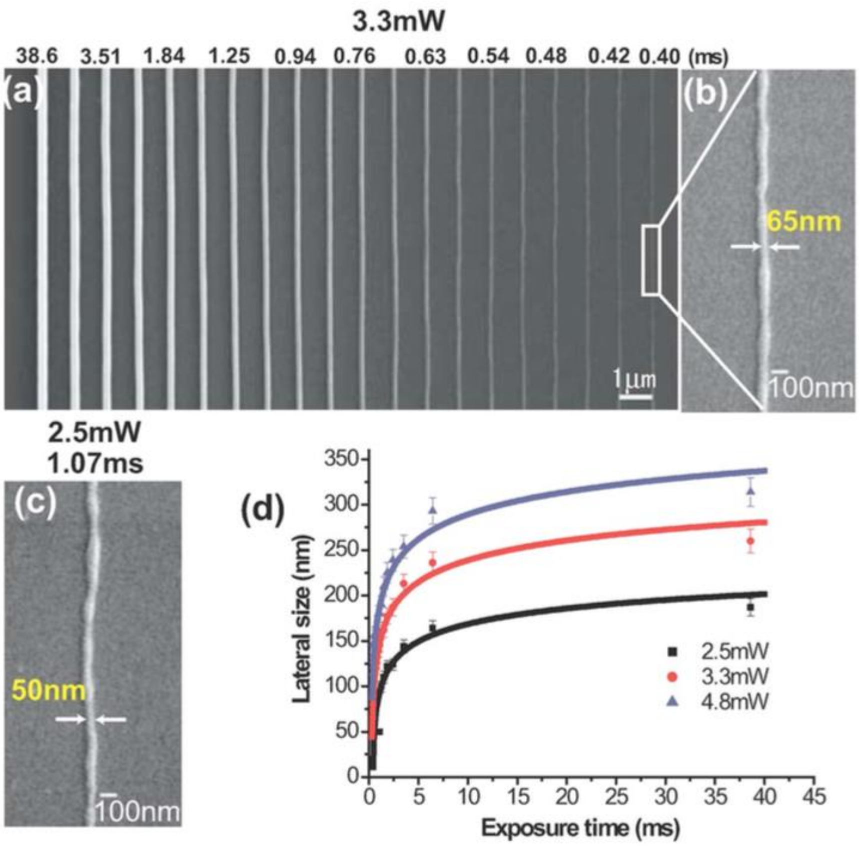
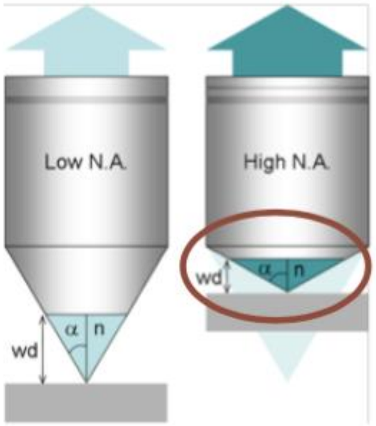
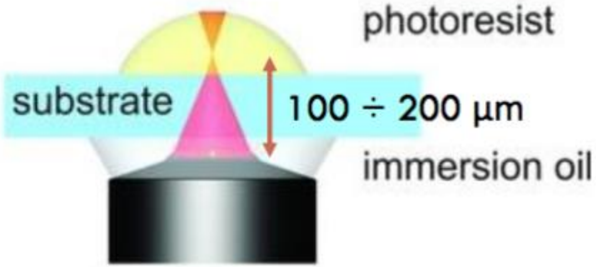


FIG. 2. (Color online) (a) SEM images of photocured polymer lines obtained using a laser power of 3.3 mW, after various exposure times. (b) Enlarged image of a line fabricated with a laser power of 3.3 mW and an exposure time of 0.4 ms. (c) A polymer line with a width of 50 nm. (d) LSR vs exposure time under different laser powers (lines are calculated results).

Height Limitation of 3D structures





E.G.: Zeiss Objective Plan-Apochromat 63x/1.40 Oil DIC

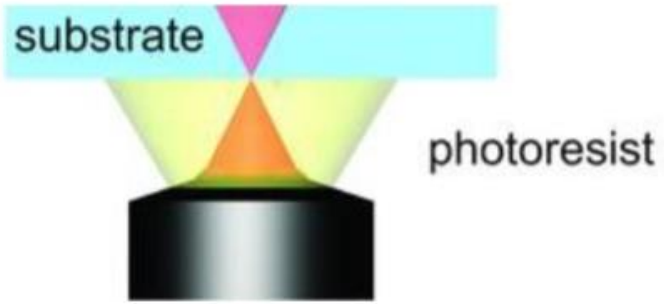
- M=63x
- NA=1.4
- WD=190 µm

Max height ~10 µm

DW: Working distance of the microscope objective i.e
The distance between the objective and the focal distance

Dip-in mode

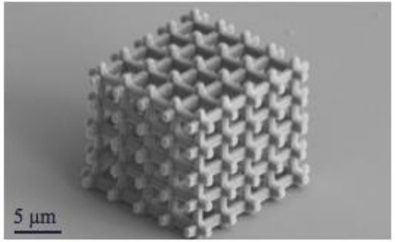
- DIP-IN

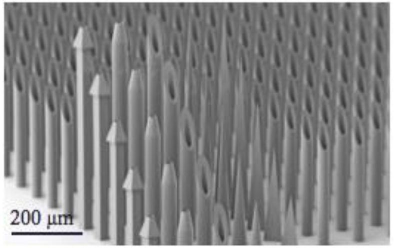


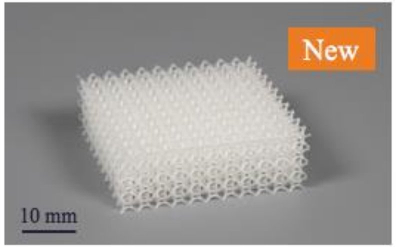
Only photoresists with matched n can be used

T. Bückmann et al., Adv. Mater., **24** 2710-2714(2012)

Dip-in mode



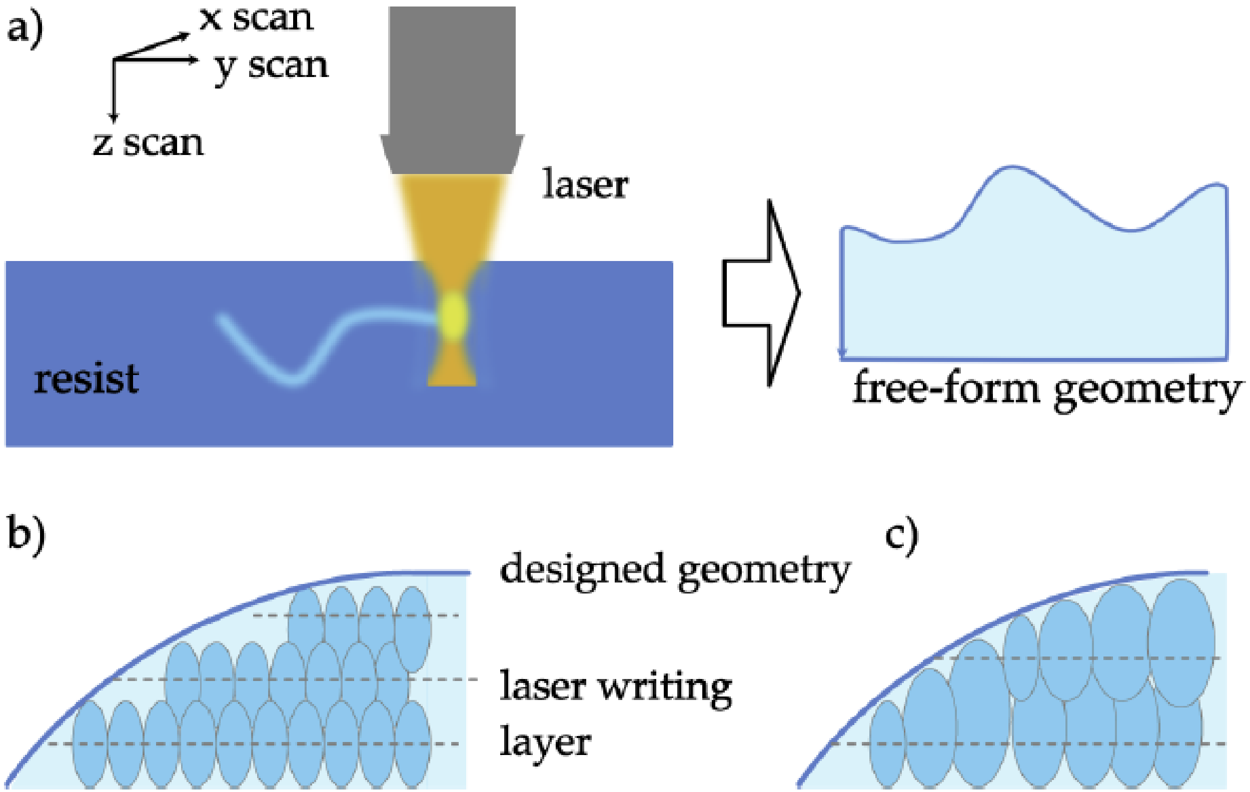




	Small feature	Medium feature	Large features	Extra large feature
Magnification NA	63x 1.4	25x 0.8	10x 0.3	5x 0.16
Calibrated print field diameter	270 µm	700 µm	1,750 µm	3,200 µm
Working distance	360 µm	380 µm	2,600 µm	18,500 µm
Scan speed (max.)	100 mm/s	250 mm/s	625 mm/s	1,250 mm/s
Slicing range (typical)	0.1 – 0.8 µm	0.5 – 3 µm	2 – 10 µm	5 – 100 µm

Two-photon polymerization (2PP)

Two-photon grayscale lithography (2GL)



2GL on Aspherical Singlet and Doublet

Research Article Vol. 31, No. 3 / 30 Jan 2023 / Optics Express 4179

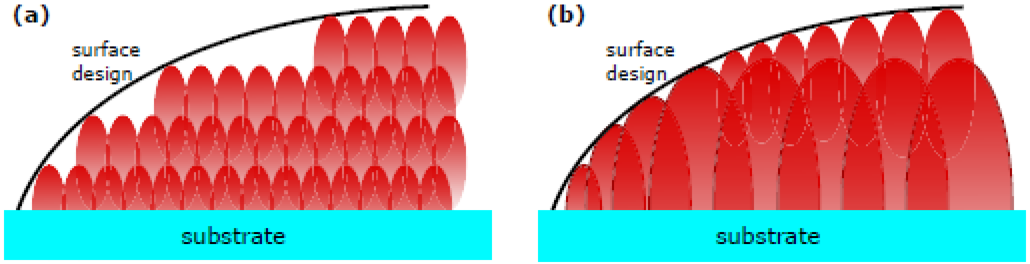
Optics EXPRESS

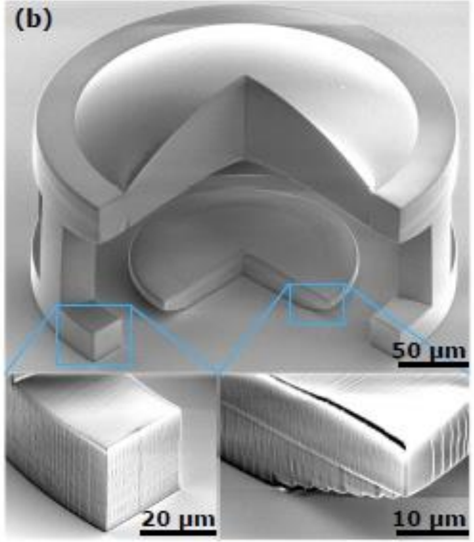
Complex aspherical singlet and doublet microoptics by grayscale 3D printing

LEANDER SIEGLE,* SIMON RISTOK, AND HARALD GIESSEN

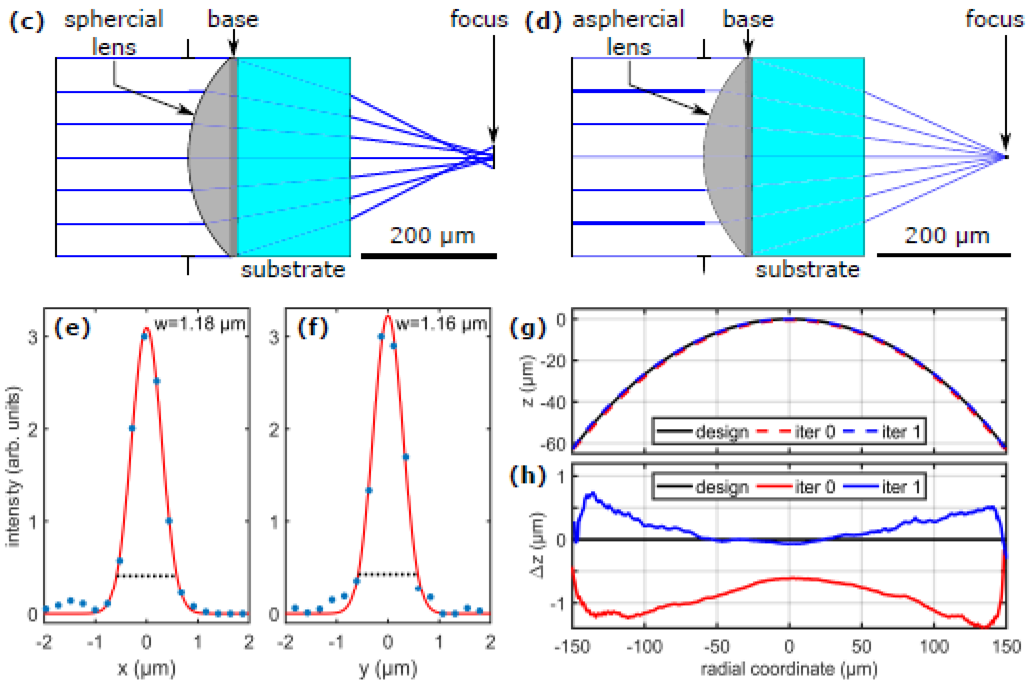
4th Physics Institute and Research Center SCoPE, University of Stuttgart, Pfaffenwaldring 57, 70569 Stuttgart, Germany

*l.siegle@pi4.uni-stuttgart.de



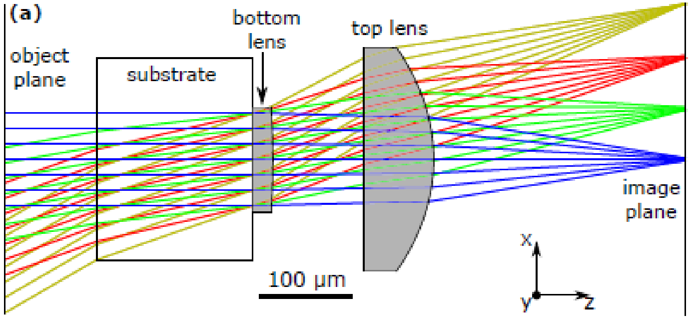


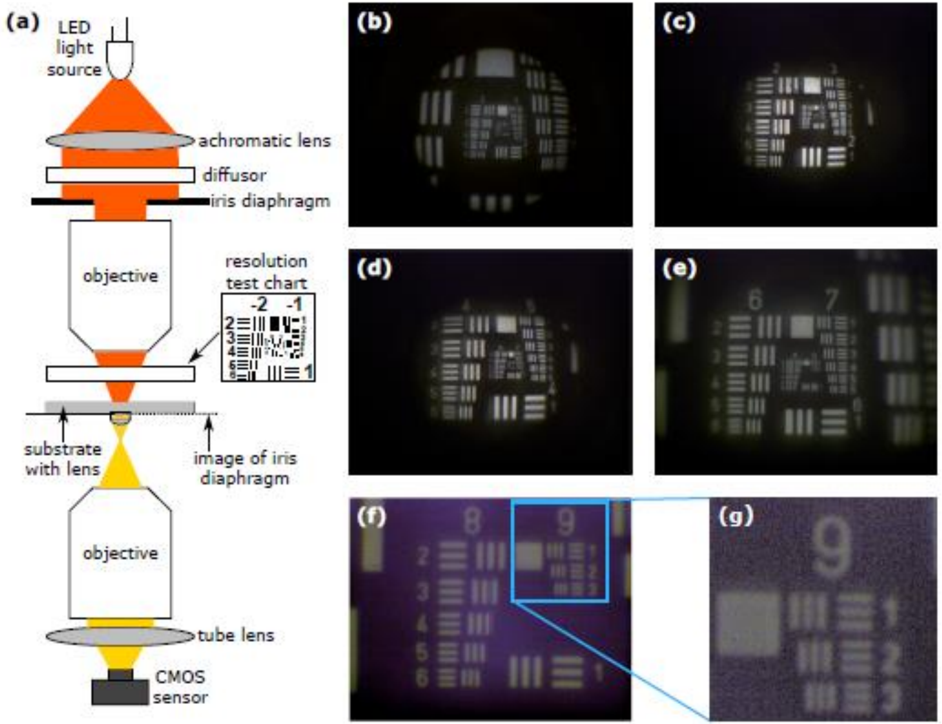
2GL on Aspherical Singlet and Doublet



https://doi.org/10.1364/OE.480472

2GL on Aspherical Singlet and Doublet



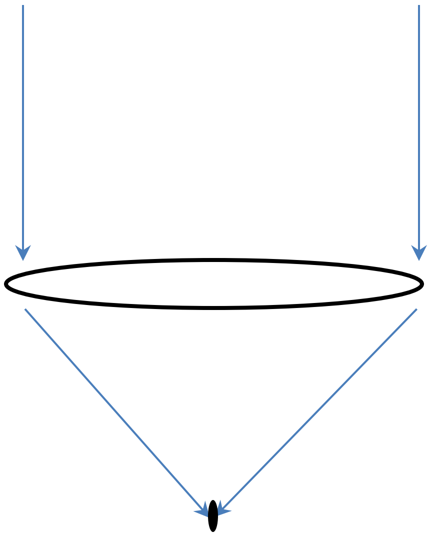


field of view of 60°
deviations 20 nm for the bottom lens
deviations 100 nm for the larger top lens
resolution 645 lp/mm

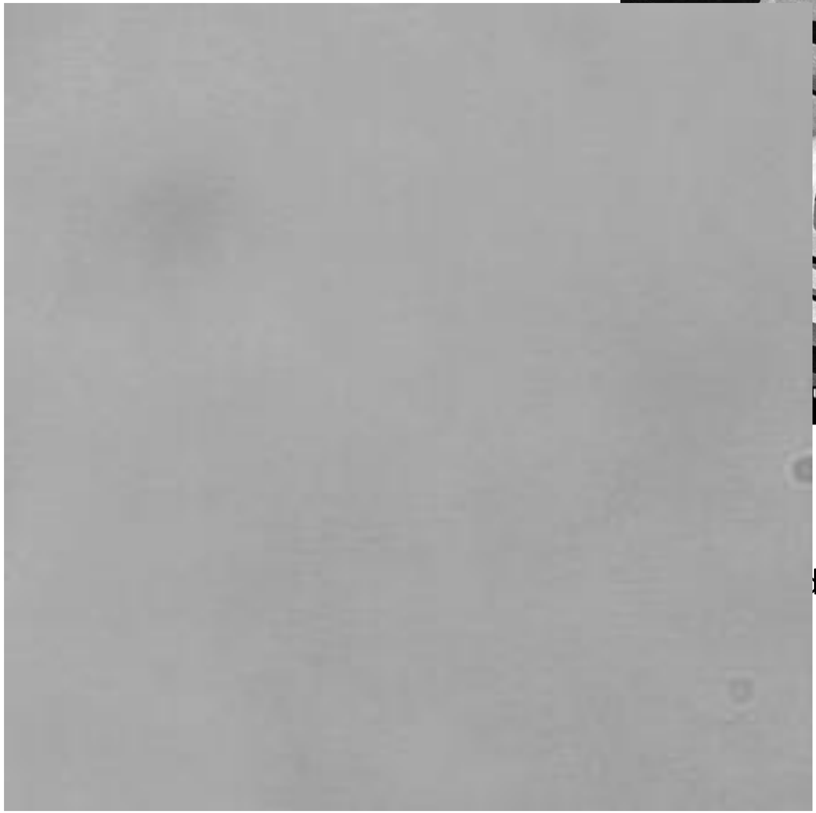
https://doi.org/10.1364/OE.480472

How to increase printing speed ?

Holographic multi-focus 3D two-photon polymerization with real-time calculated holograms – Optics Express 2014

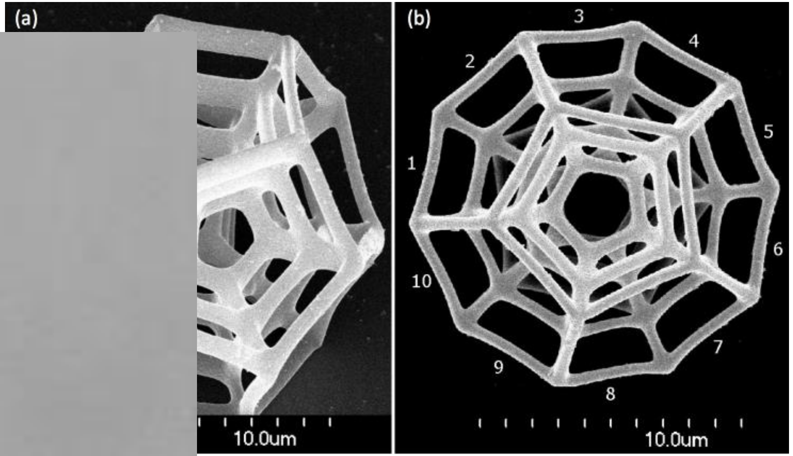


Single focus



This can be generated by a DLP for example

into



Fabricated by 550 projections giving each 5 Foci.

Example: bio-printing

5 ms exposure, 3 mW/foci → 200 Hz
750 foci → 2.2 W

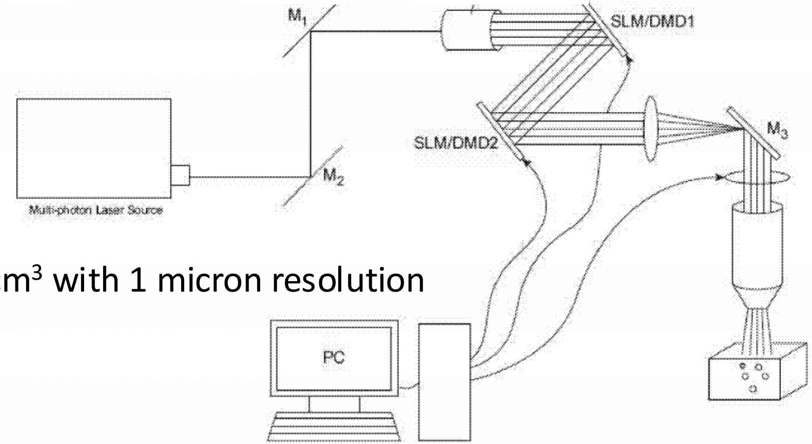
150,000
Voxels/second

(19) **United States**
(12) **Patent Application Publication**
MATHEU

(54) **METHODS AND SYSTEMS FOR PRINTING BIOLOGICAL MATERIAL**

(71) Applicant: **Prellis Biologics, Inc.**, San Francisco, CA (US)

(52)



Time to print 1 cm^3 with 1 micron resolution

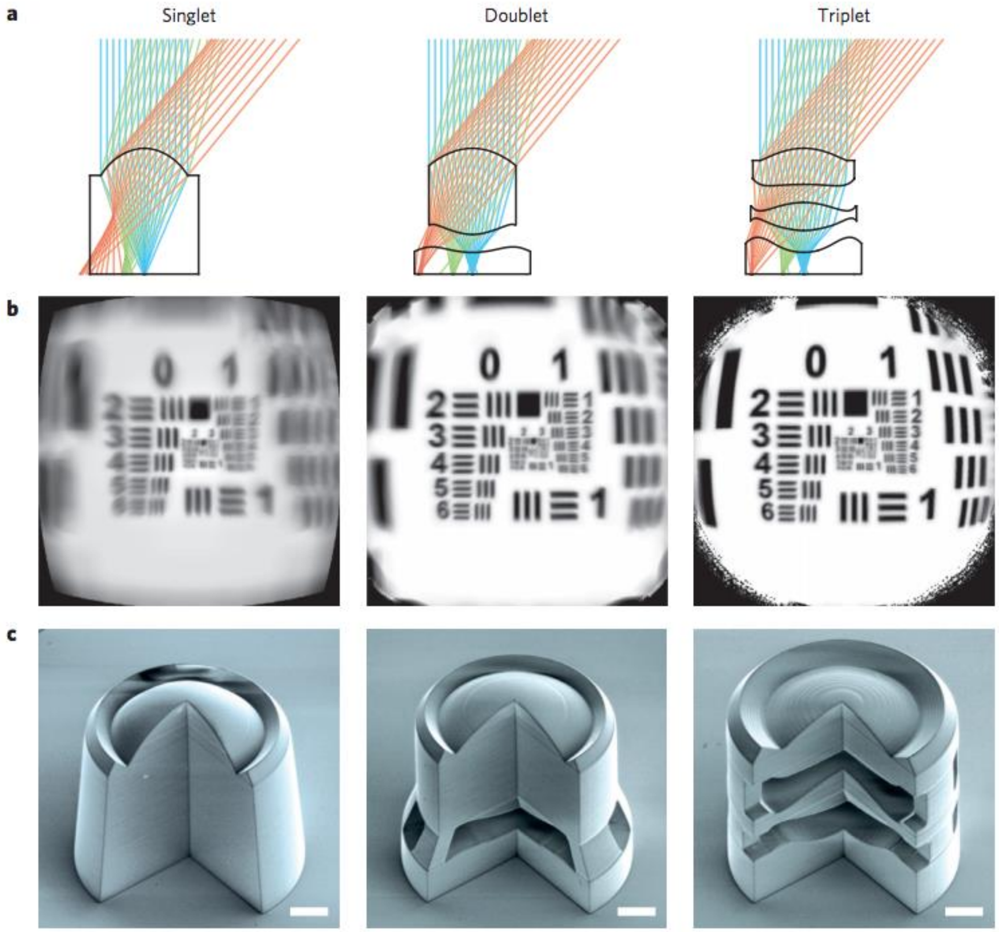
$$fab\ time = f \cdot n_{voxels}/\#voxels/sec$$

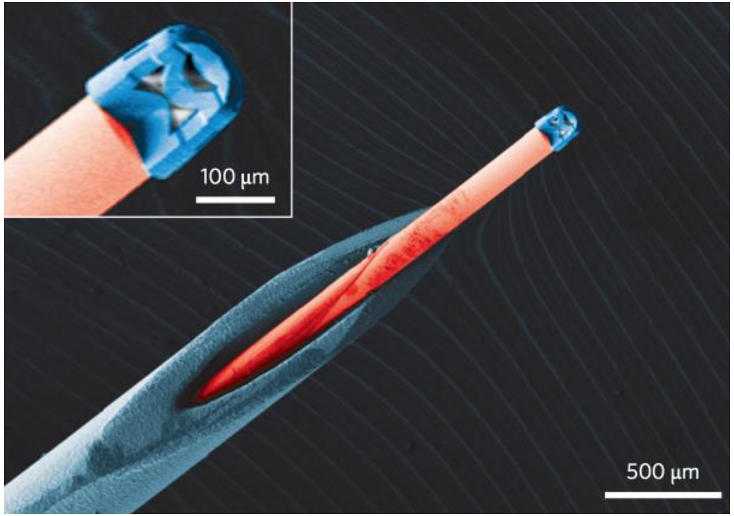
Fill factor 1%	15%
18.5 h	11.5 days

Two-photon direct laser writing of ultracompact multi-lens objectives

nature photonics

EPFL

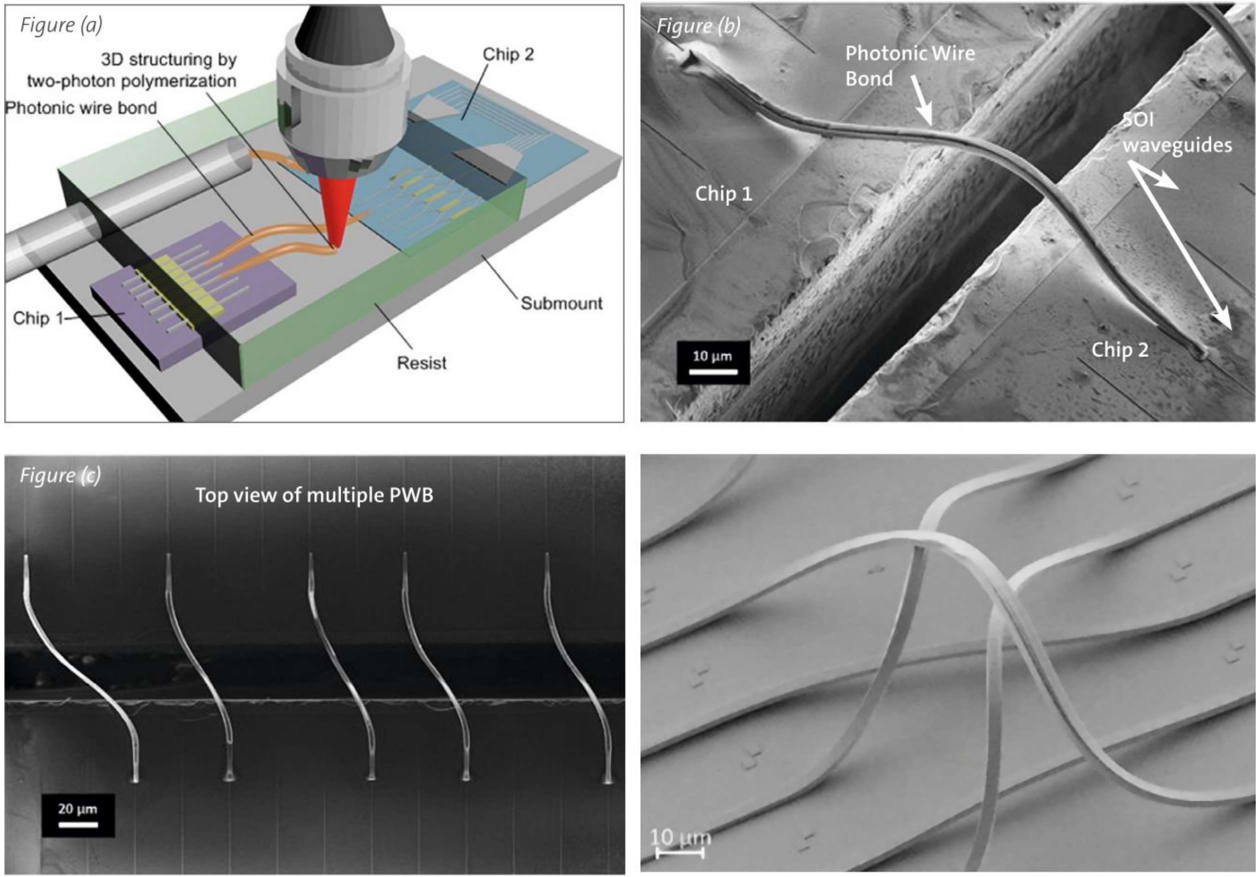




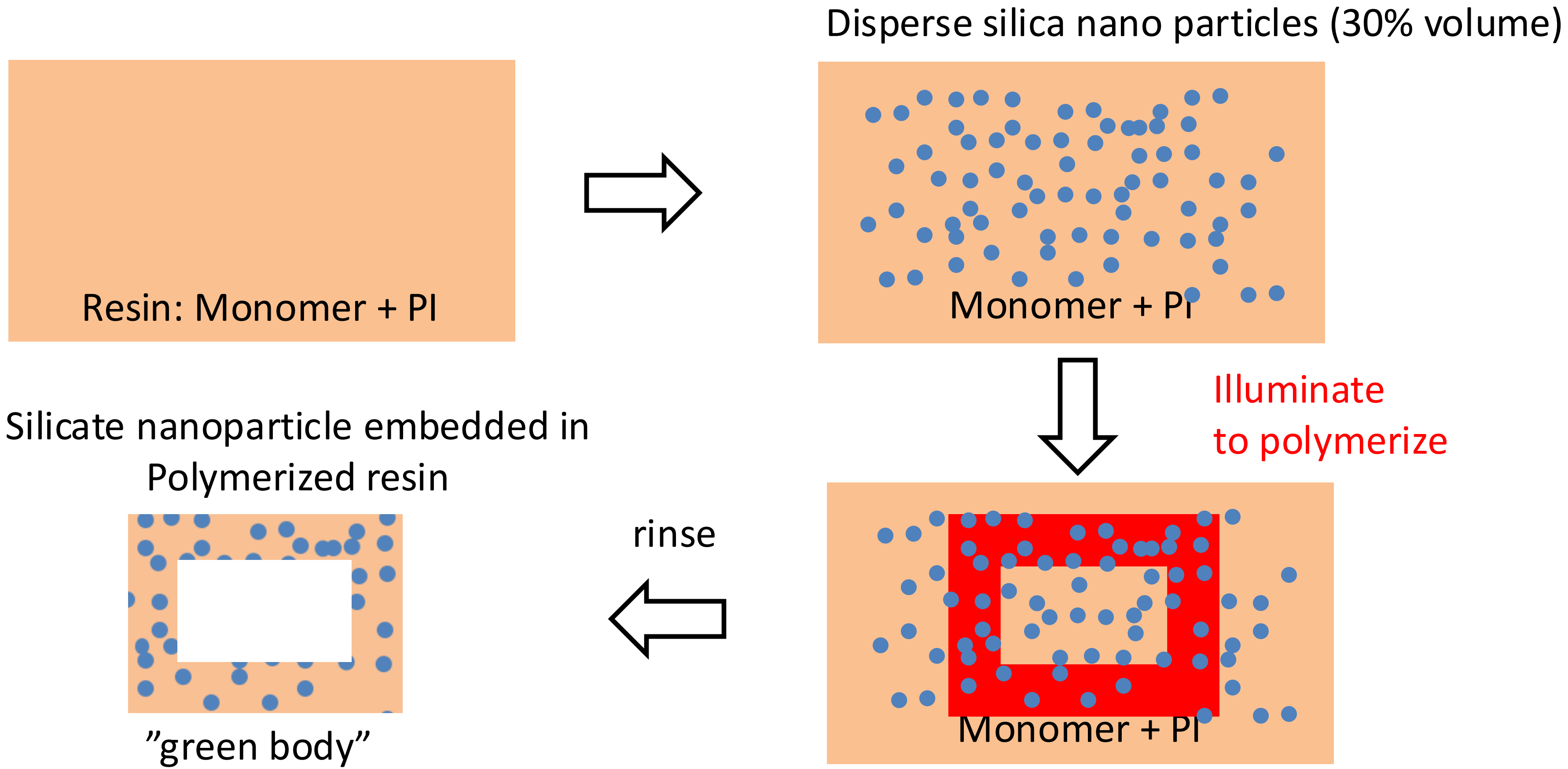
Transparent polymer material

Photonic Wire bonding

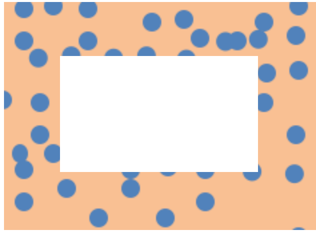
Vol. 20, No. 16 / OPTICS EXPRESS 2012



2 Photon Polymerization : glass



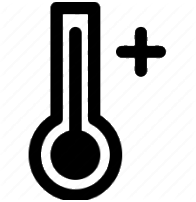
2 Photon Polymerization : glass

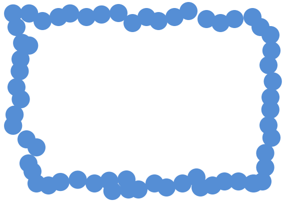


"green body"

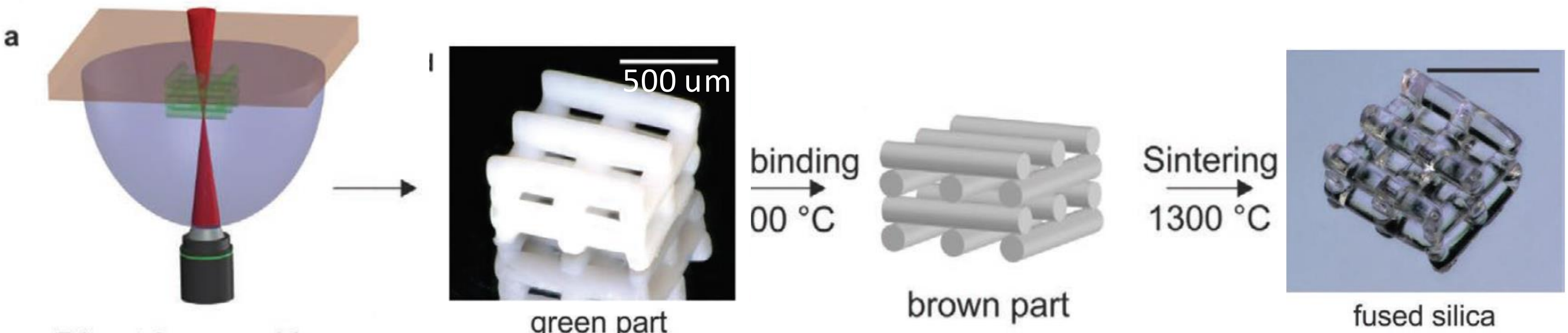
oven

1300°C



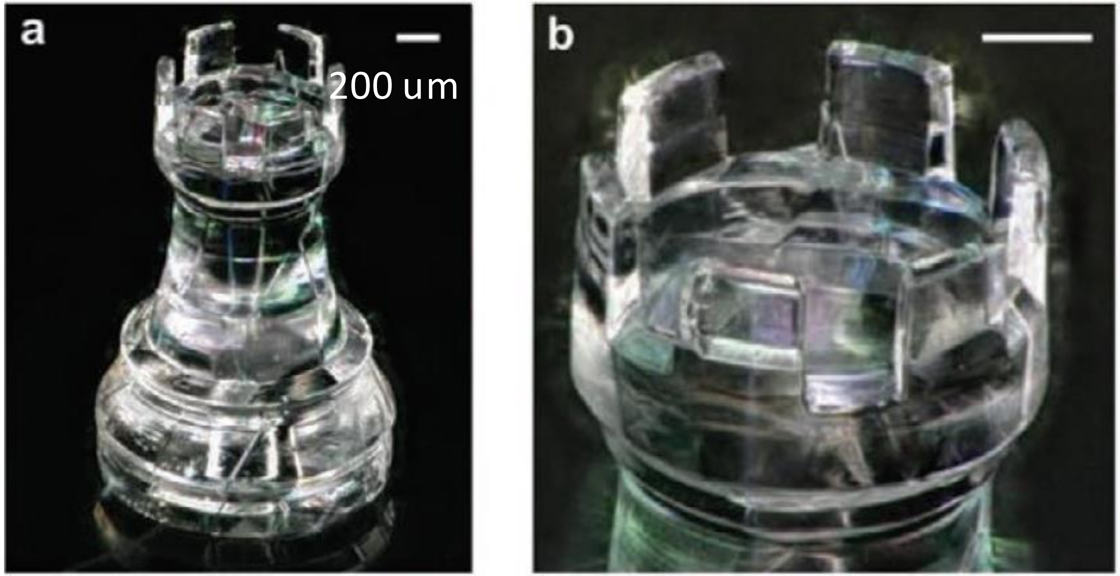


The silica particles sinter and
the polymer are vaporized by the heat
Leaving only the merged silicate particles



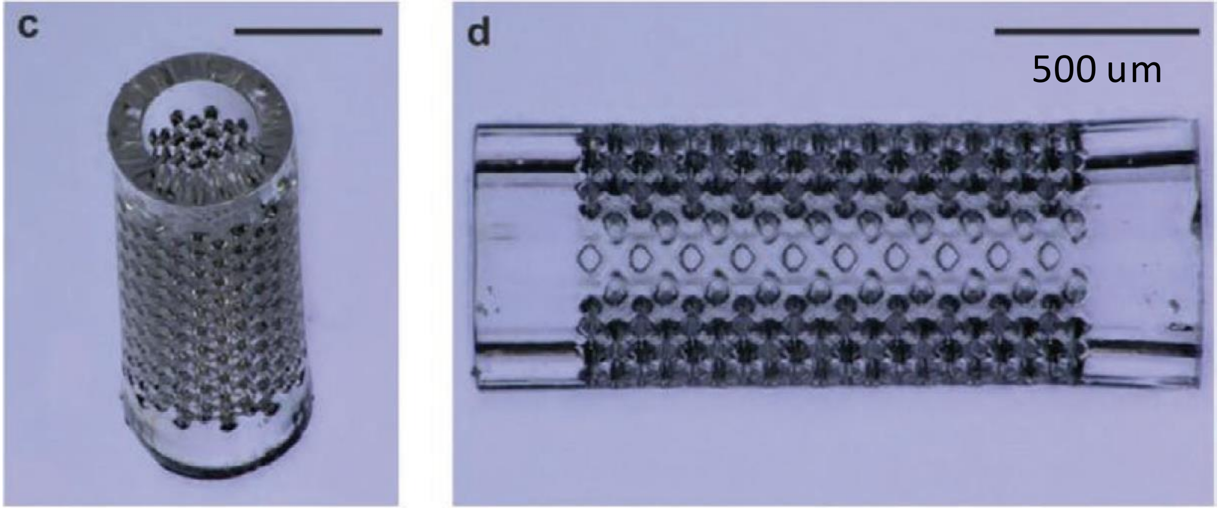
Direct laser writing=2 Photon Polymerization

Micro glass prints



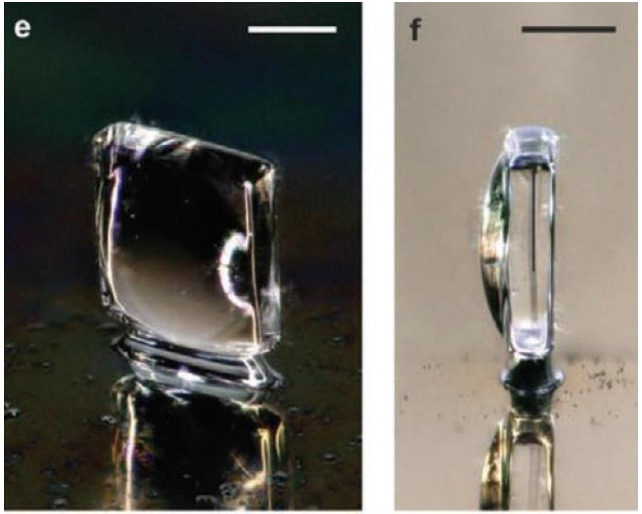
Slicing 5 µm, hatching 1 µm, scan speed 100 mms^{-1}

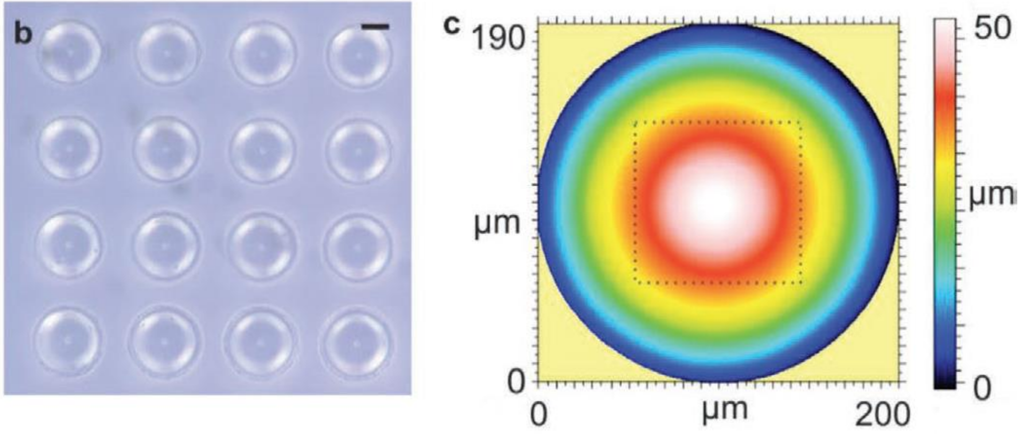
Micro glass prints



Micro filter element with 55 um holes

Slicing 5 µm, hatching 1 µm, scan speed 100 mms^{-1}



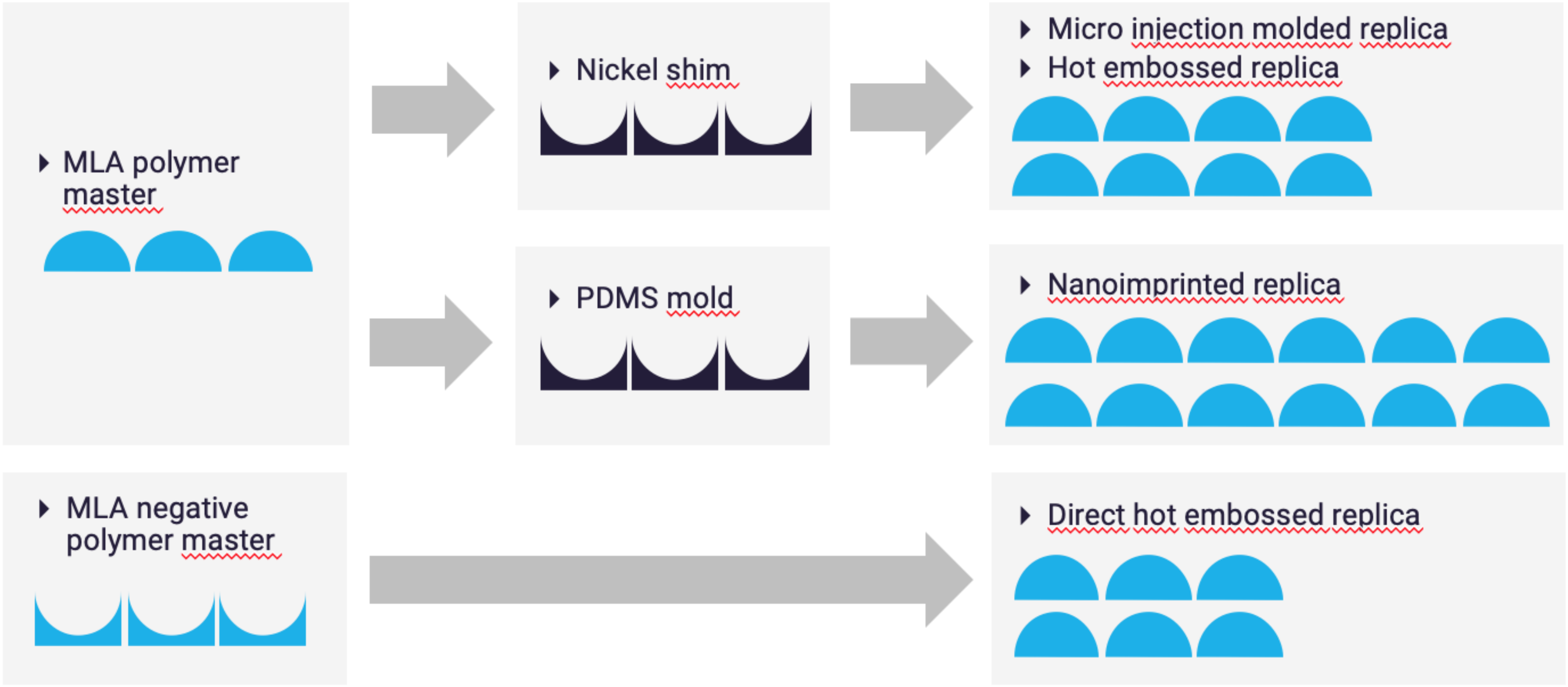


Glass micro lenses

Surface roughness Ra ≈ 6.1 nm

High precision parts for replication

Replication processes
From polymer master to small series production



2-photon
Printer
By Nanoscribe

At Cmi
BM building