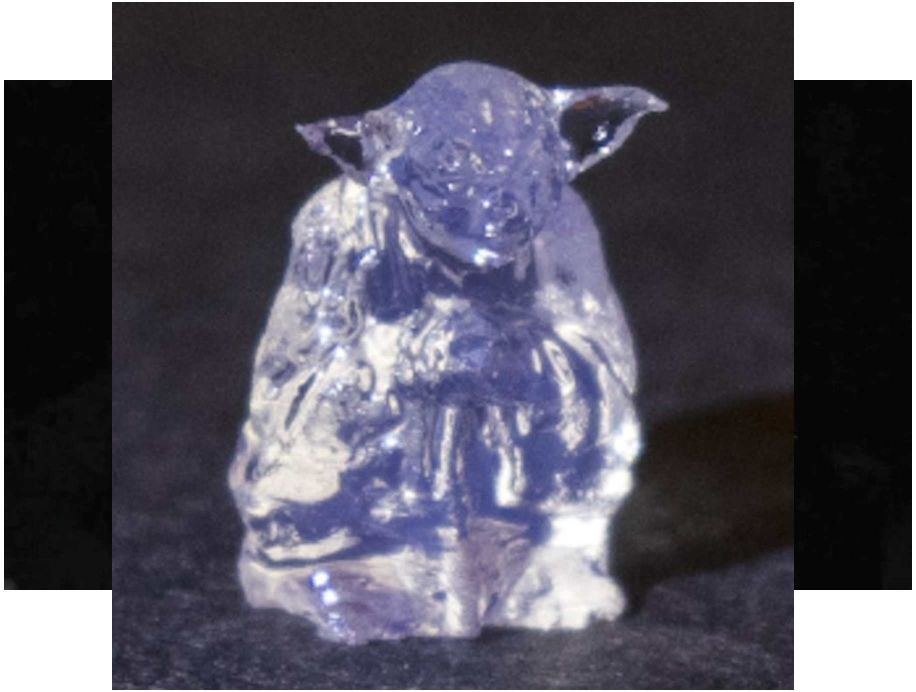
Modules of the 2025 course

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

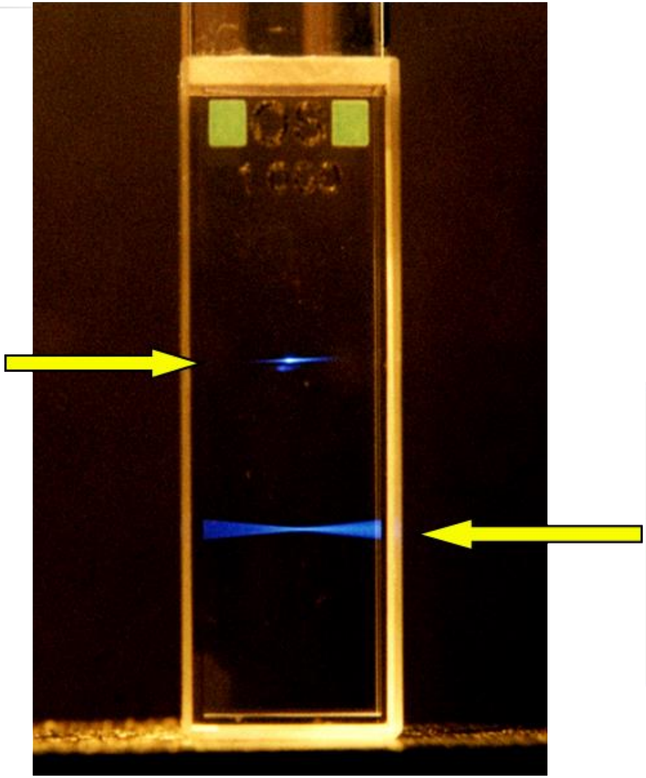
QUIZZ #2

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

Example: 2 photons infrared of wavelength $\lambda_1 = 800\,nm$ ($\nu_1 = c/\lambda_1$) have a combined energy of $E = 2h\nu_1$ and can produce absorption at $\nu_2 = 2\nu_1$ ($\lambda_2 = c/\nu_2 = \frac{c}{2\nu_1} = \frac{1}{2}\lambda_1$)

# of molecules in excited state

linear absorption → α $[\frac{1}{m}]$

$$\frac{dN_1\text{, one photon}}{dt} = +\overbrace{\sigma\, N_{GS}}^{\alpha}\cdot\frac{I}{h\nu}$$

$[m^2]$

one photon cross-section

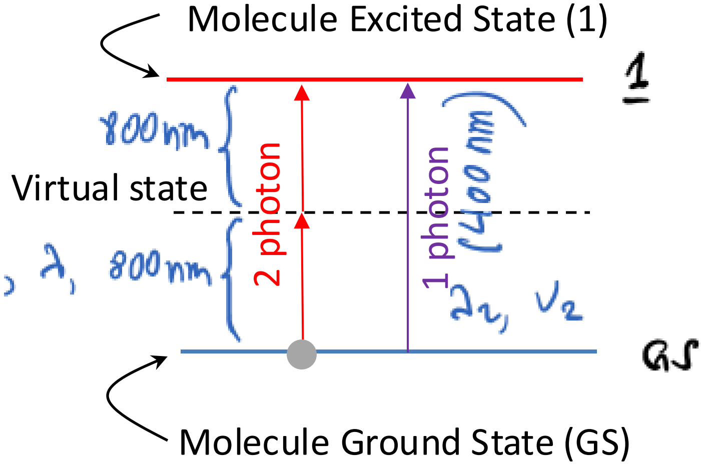
$$\frac{dN_1\text{, two photon}}{dt} = \frac{1}{2}\delta\; N_{GS}\cdot\boxed{\frac{I^2}{(h\nu)^2}} = \frac{1}{2}\overbrace{\delta\,\frac{N_{GS}}{h\nu}}^{\beta}\,\frac{I^2}{h\nu}$$

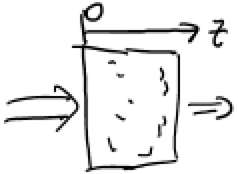
$[m^4 \cdot s]$

two-photon cross-section

$1\,GM = 10^{-50}\,[cm^4 \cdot s]$

Goeppert-Mayer





In terms of absorption for the light intensity

Single photon $$\frac{dI(z)}{dz} = -\alpha_{400} \cdot I(z) \Rightarrow I(z) = I(0)\, e^{-\alpha z}$$ $\lambda_1 = 400\,nm$

Two photon $$\frac{dI(z)}{dz} = -\alpha_{800} \cdot I(z) - \boxed{\beta I^2(z)}$$ $\lambda_2 = 800\,nm$

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

$$\alpha I \simeq \beta I^2 \Rightarrow \alpha = \beta I \Rightarrow I = \frac{\alpha}{\beta}$$

$$I = 2\frac{\sigma}{\delta} h\nu = 2\frac{\sigma}{\delta} h\frac{c}{\lambda}$$

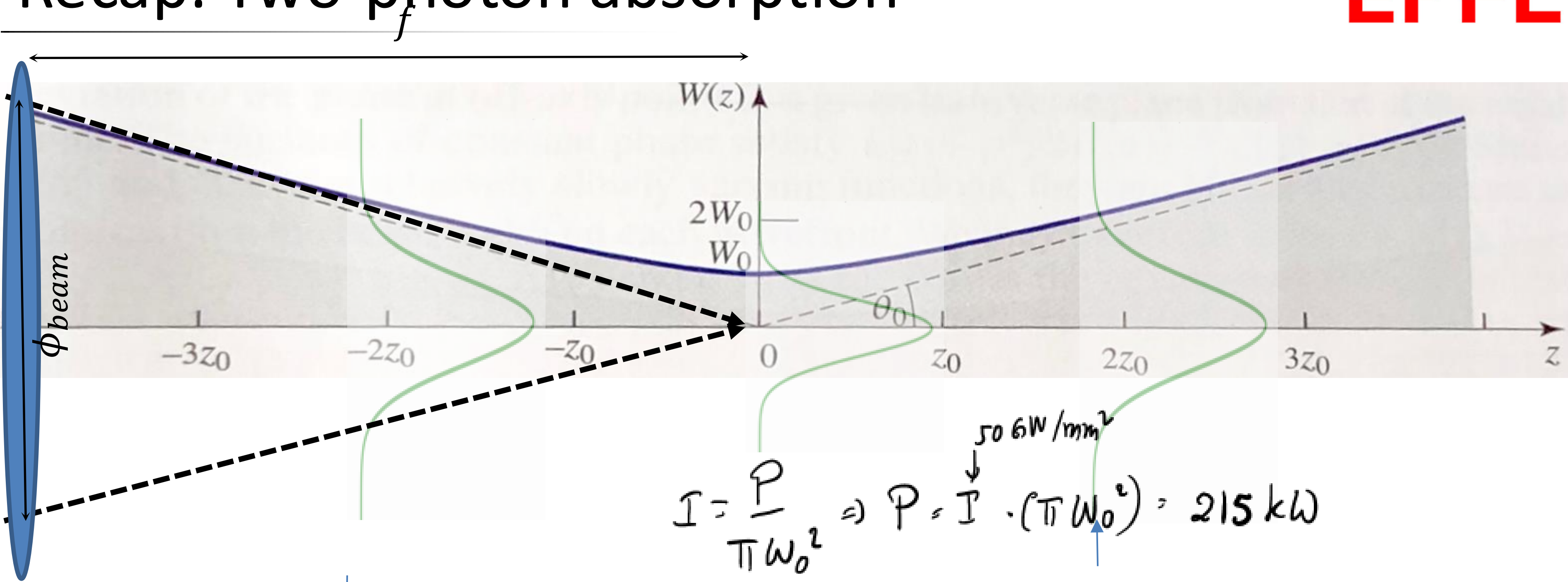
Typ. Values

cross section 1 photon $\nearrow$ $\sigma \simeq 10^{-16}\,cm^2$

Xsection 2 phot. $\nearrow$ $\delta = 1000\,GP = 1000 \cdot 10^{-50}\,[cm^4 . s]$

$$\boxed{I \simeq 50 \cdot 10^9 \frac{W}{mm^2}} = 50\,GW/mm^2$$

Recap: Two-photon absorption



50 GW/mm²

$$I = \frac{P}{\pi W_0^2} \Rightarrow P = I \cdot (\pi W_0^2) = 215\,kW$$

$$W_0 = 0.66 \cdot \frac{\lambda}{NA} = 1.17\,\mu m$$

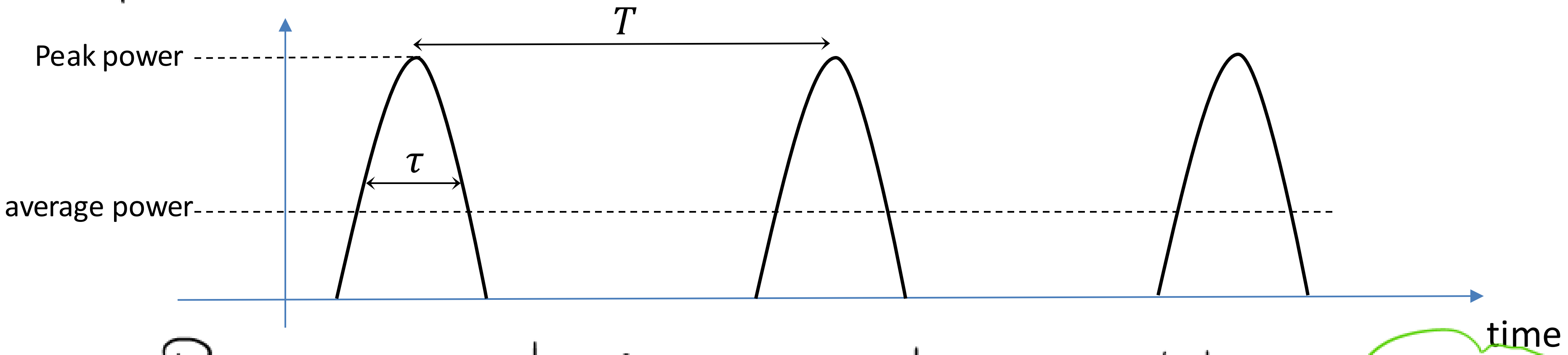
0.2

Two-photon absorption

How to generate a laser power of ~~860~~ 215 kW ?

Ans: pulsed laser

Ans: pulsed power



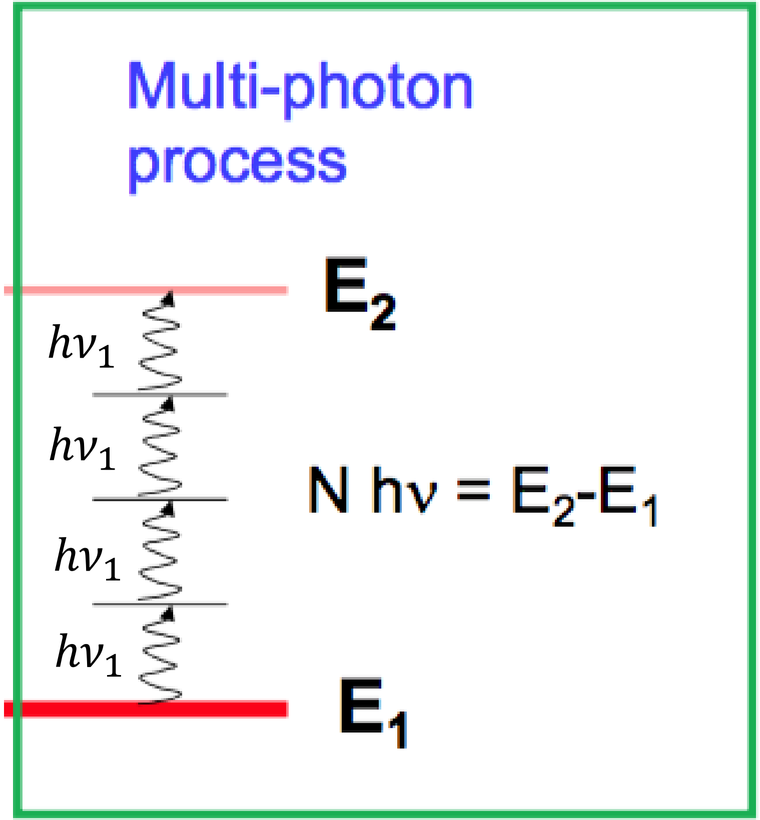
$$P_{average} = \frac{\text{average laser energy}}{\text{time}} = \frac{\#\text{pulses} \cdot \text{energy/pulse}}{\text{time}} = 1\,\frac{\boxed{\text{energy/pulse}}}{T}$$

$$P_{peak} = \frac{\boxed{\text{energy/pulse}}}{\tau} = P_{average} \cdot \frac{T}{\tau}$$

Multi-photon absorption

A material is transparent at a wavelength of λ_1 $(\lambda_1 \cdot \nu_1 = c)$ (i.e frequency $\nu_1 = c/\lambda_1$) but can become absorptive at very high optical peak powers

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



Two-photon absorption

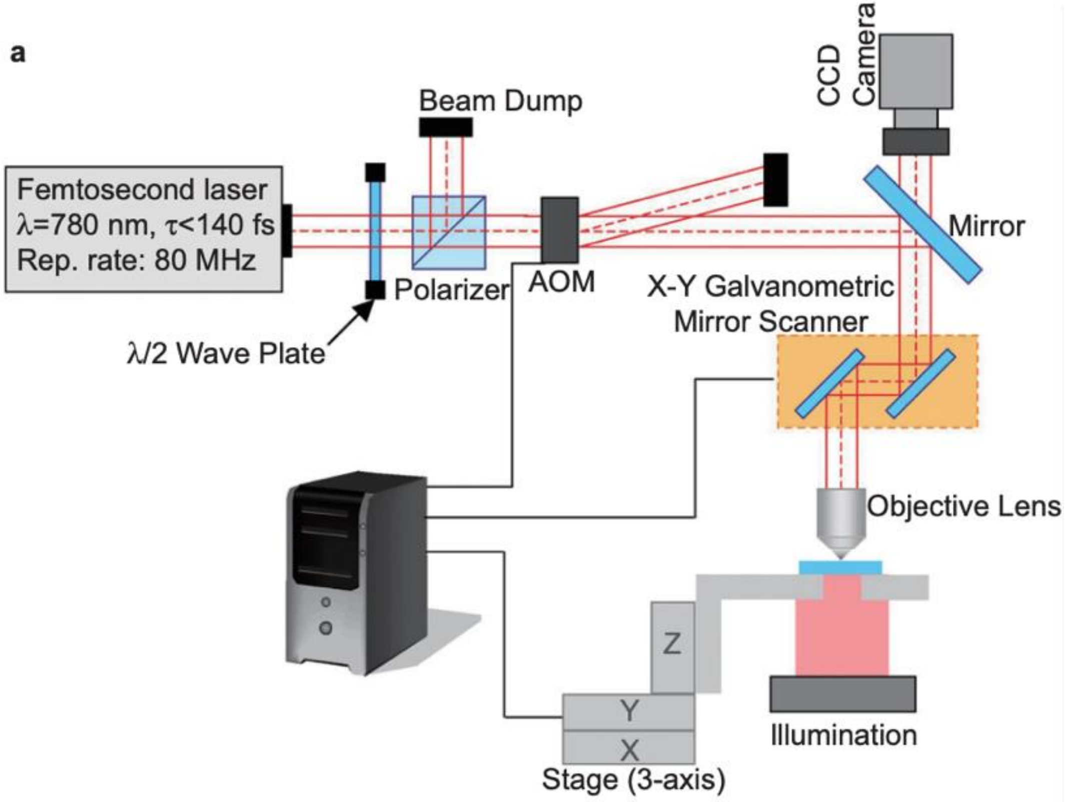
		τ	$P_{average}$	$1/T$	
FemtoFiber smart 780	785 ± 5 nm	< 100 fs (typ. 80 fs)	> 120 mW (typ. 140 mW)	80 MHz	16

$100 \cdot 10^{-15}\ s$

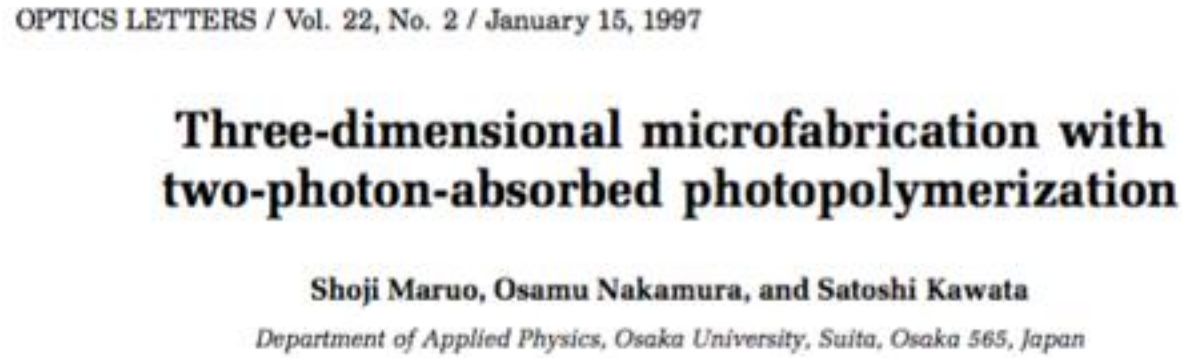
$$P_{peak} = P_{average} \cdot \frac{T}{\tau} = 0.12\,W \cdot \frac{1}{10^{-13} \cdot 80 \cdot 10^{6}} = \underline{\underline{15\,kW}}$$

$$N.A \gtrsim \underline{\underline{0.8}}$$

Typical setup for 2-photon polymerization



Original first demonstration



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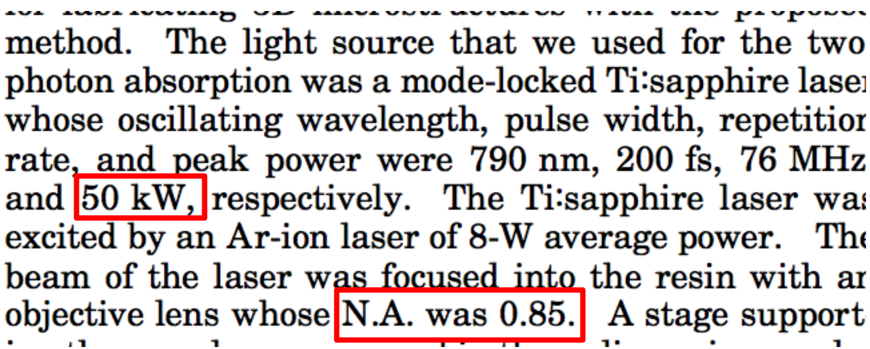
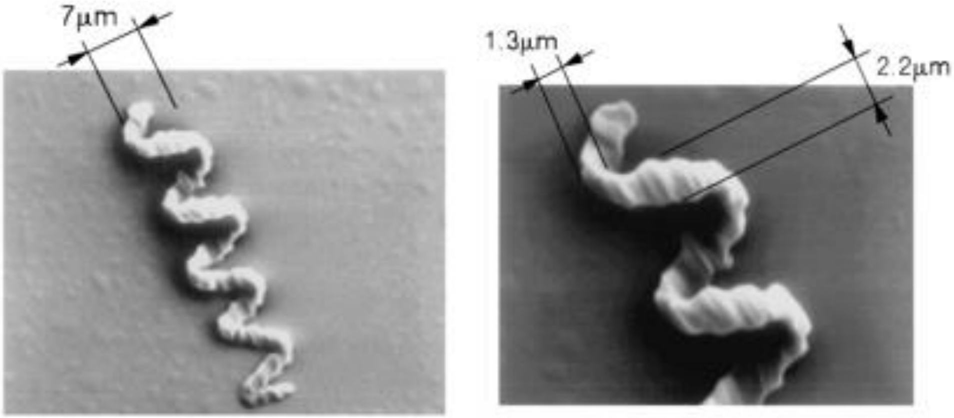
Three-dimensional microfabrication with two-photon-absorbed photopolymerization

Shoji Maruo, Osamu Nakamura, and Satoshi Kawata

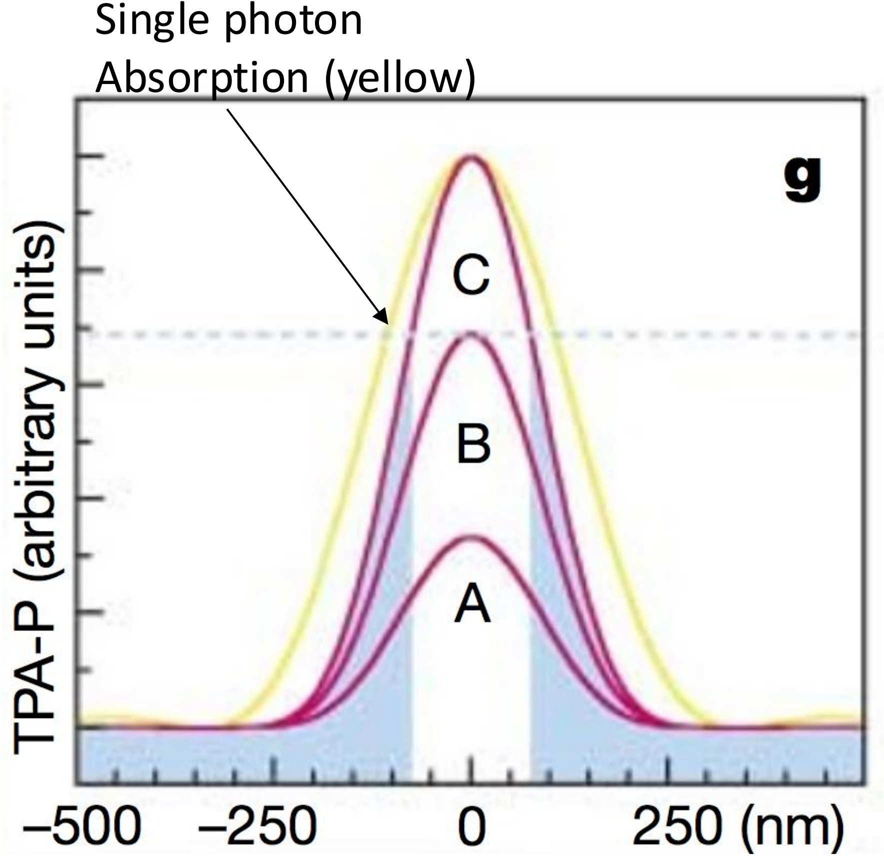
Department of Applied Physics, Osaka University, Suita, Osaka 565, Japan

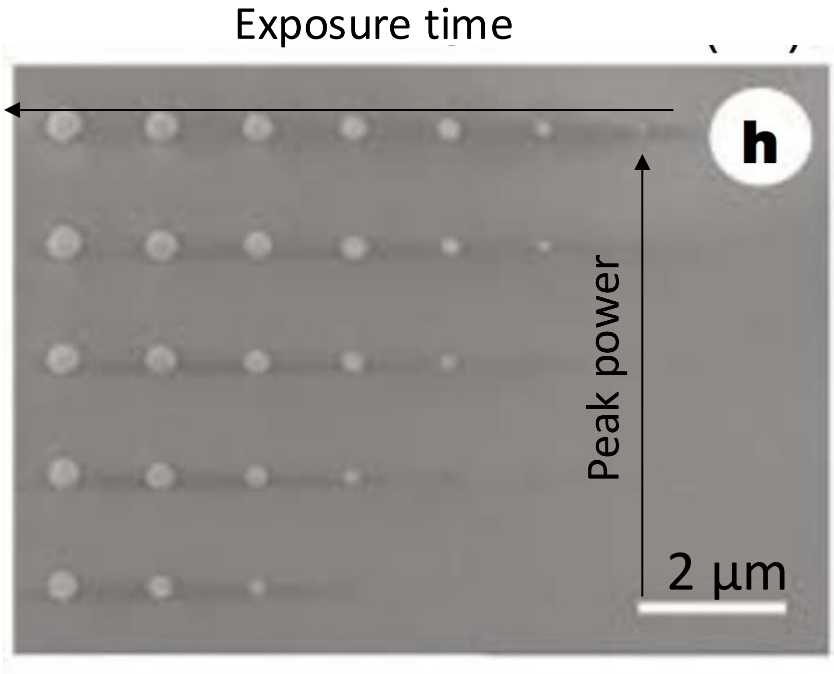


method. The light source that we used for the two photon absorption was a mode-locked Ti:sapphire lase whose oscillating wavelength, pulse width, repetitio rate, and peak power were 790 nm, 200 fs, 76 MHz and 50 kW, respectively. The Ti:sapphire laser wa excited by an Ar-ion laser of 8-W average power.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



Printed voxel size





Printed voxel size

Energy per pulse: E_{pulse} =137 pJ

Pulse duration: τ =150 fs

$$P_{peak} = \frac{E_{pulse}}{\tau} = \frac{137 \cdot 10^{-12}}{150 \cdot 10^{-15}}$$

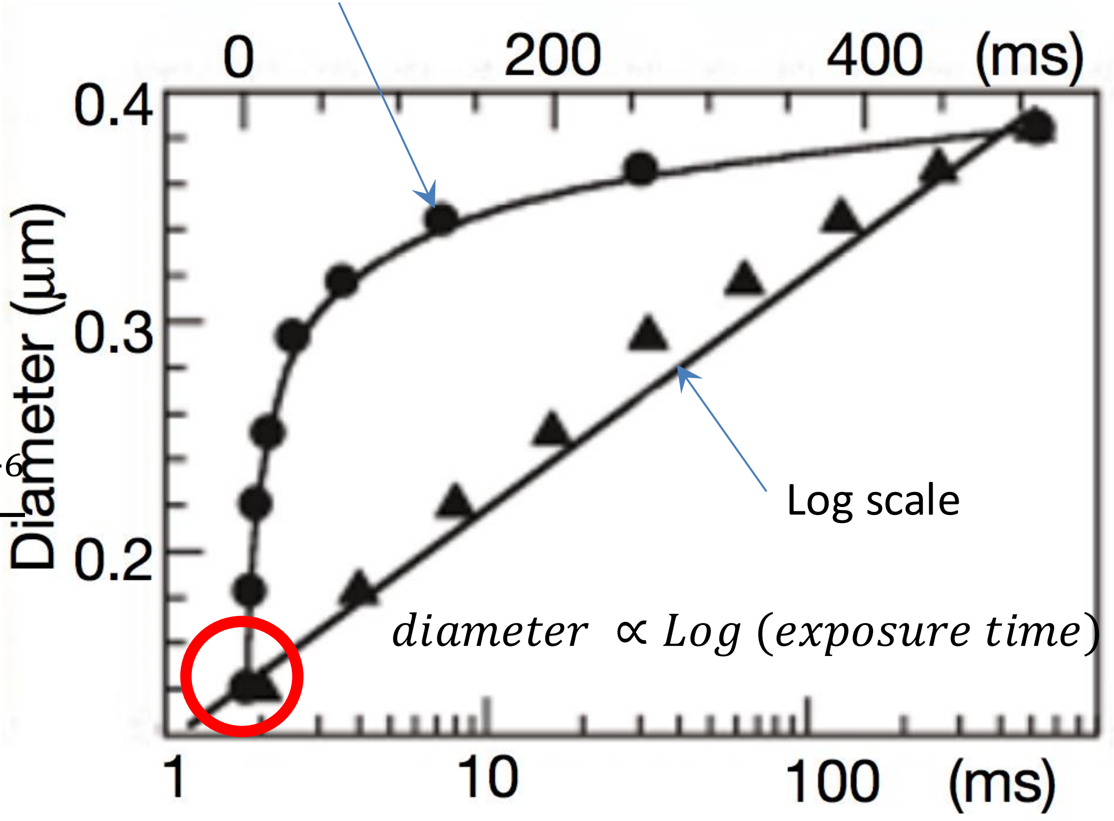
=910 W (10 mW average power)

Numerical aperture NA=1.4

$$waist = 0.66\,\frac{\lambda}{NA} = \frac{0.66 \cdot 0.8 \cdot 10^{-6}}{1.4}$$

$$= 0.37\ \mu m$$

$$I = \frac{P_{peak}}{\pi \cdot waist^2} = 2.1\ GW/mm^2$$



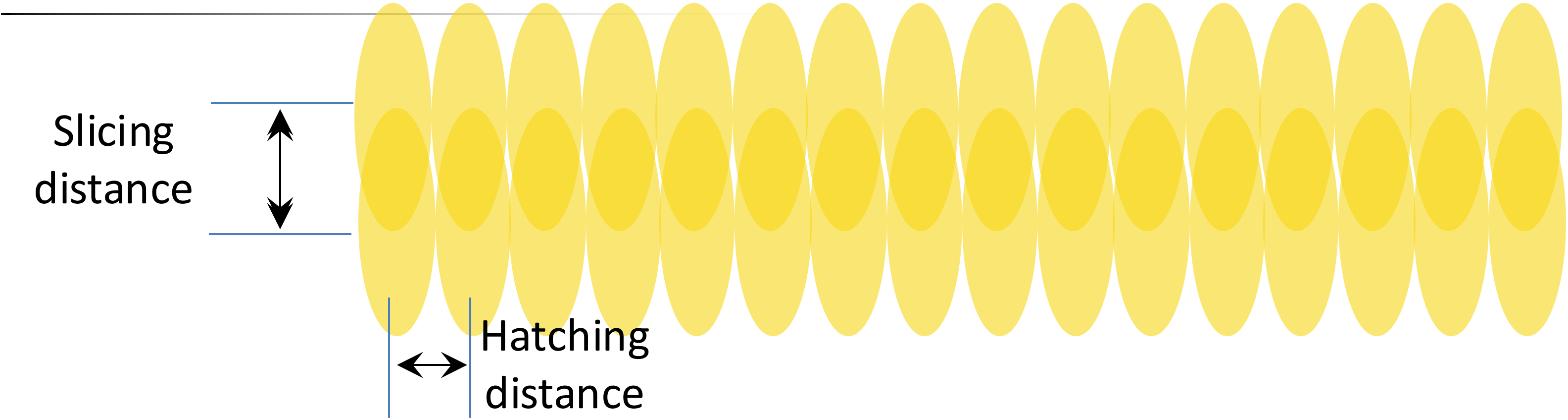
Linear scale

Log scale

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

Exposure time

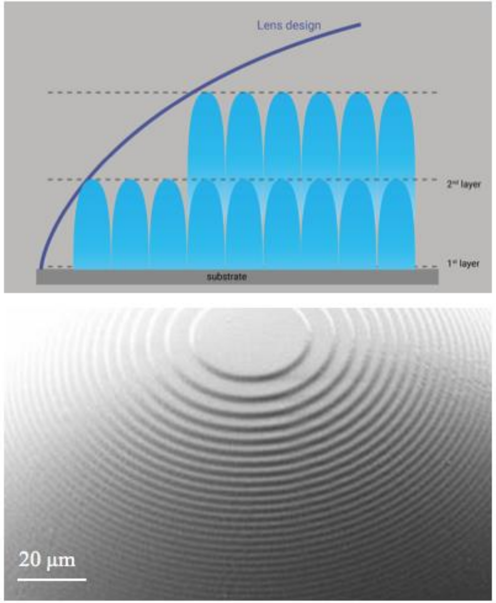
Fabrication time depends also on the scanning step



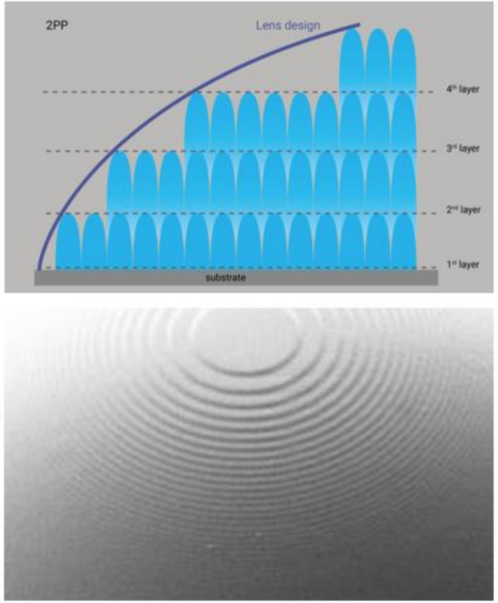
Scanning steps can be smaller to make a smooth surface

Challenge in high-precision 3D printing

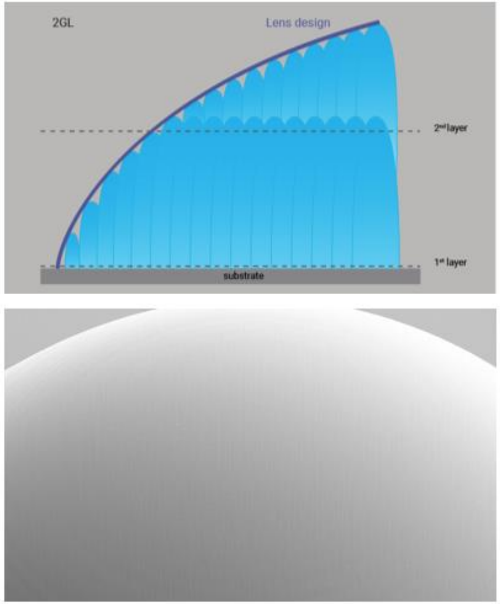
Staircasing vs. printing speed



2PP with coarse slicing



2PP with fine slicing



2GL® with coarse slicing

Courtesy of NanoScribe

Example:
20 x 20 x 20 um

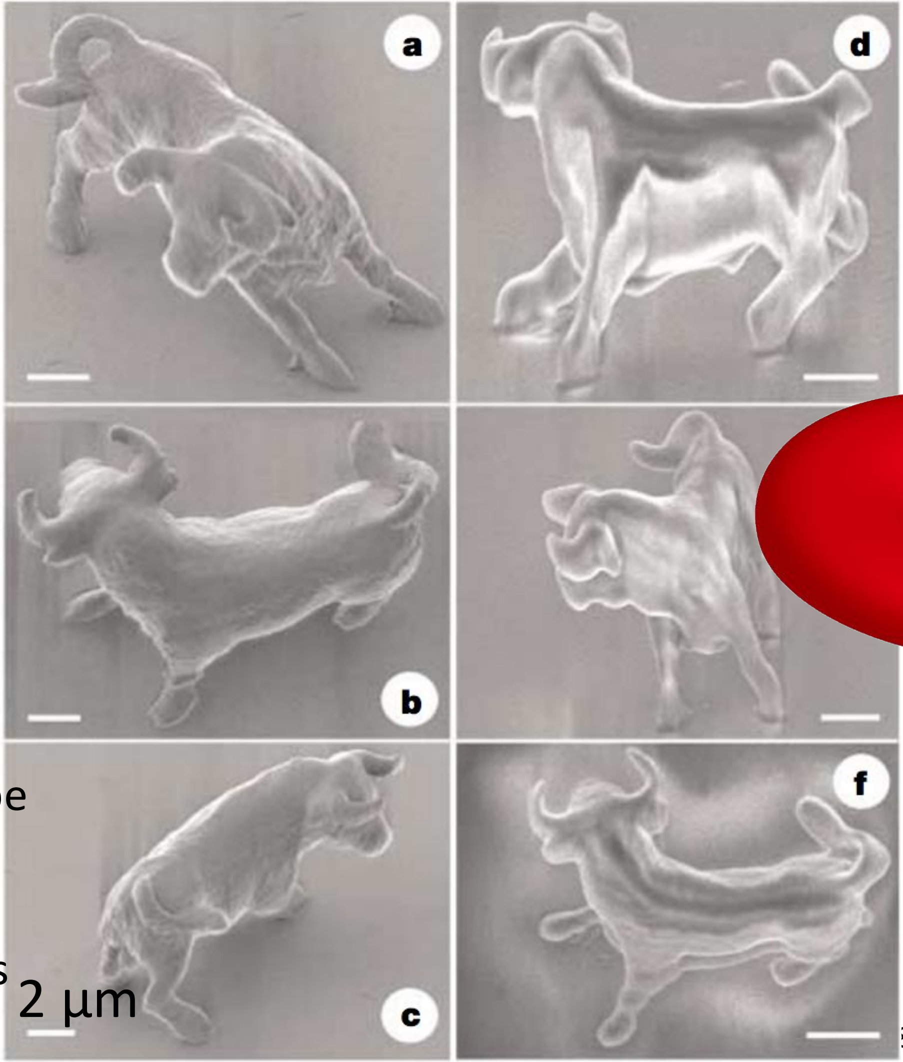
2 ms exposure
Hatching-slicing (x,y,z): 0.15 um.

$$\#points = \frac{20^3}{0.15^3} = 2.4\ million$$

$$Exposure\ time = 1h\ 20\ min$$

If only the outer shell of the bull is Printed, the number of points can be Reduced.

The authors printed it in 13 minutes



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A red blood Cell for comparison