

Holographic 3D laser nanoprinting at the speed of light

Paul Somers

Paul.Somers@kit.edu

Karlsruhe Institute of Technology (KIT) <https://orcid.org/0000-0002-1674-5408>

Sebastian Koch

Karlsruhe Institute of Technology (KIT) <https://orcid.org/0009-0009-0970-1835>

Markus Nyman

Karlsruhe Institute of Technology (KIT)

Josephine Spiegelberg

Karlsruhe Institute of Technology (KIT) <https://orcid.org/0009-0002-0313-1404>

Maryna Meretska

Karlsruhe Institute of Technology <https://orcid.org/0000-0001-8749-9374>

Carsten Rockstuhl

Karlsruhe Institute of Technology <https://orcid.org/0000-0002-5868-0526>

Martin Wegener

Karlsruhe Institute of Technology (KIT) <https://orcid.org/0000-0002-9770-2441>

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Title

Holographic 3D laser nanoprinting at the speed of light

Authors

Sebastian Koch, Markus Nyman, Josephine Spiegelberg, Maryna L. Meretska, Carsten Rockstuhl, Martin Wegener, Paul Somers

Affiliations

Institute of Applied Physics, Karlsruhe Institute of Technology; Karlsruhe, 76131, Germany: S.K., J.S., M.W.

Institute of Nanotechnology, Karlsruhe Institute of Technology; Karlsruhe, 76131, Germany: M.N., M.L.M., C.R., M.W., P.S.

Institute of Theoretical Solid State Physics, Karlsruhe Institute of Technology; Karlsruhe, 76131, Germany: C.R.

Main text

Light-based 3D printing processes¹ are unmatched in micro/nano-manufacturing owing to their high resolution and potential for scalability. Increases in the printing speeds of these technologies have mostly relied on parallelization approaches such as multiple laser foci^{2,3} or image projection⁴⁻⁶. Yet these directions are ultimately limited due to the need to mechanically scan the light for printing⁷. A new approach to 3D nanoprinting is therefore required to realize further substantial increases in print speed. Here, we introduce a fully parallel holographic approach that leads to peak print rates 100,000,000,000× faster than existing techniques. To achieve this breakthrough, we encode the information of a target 3D object in a single, femtosecond laser pulse via a computer-generated hologram. As the pulse then propagates through a photo-sensitive

medium, it exposes the entire complex-shaped 3D microstructure in a single shot, thereby printing at the speed of light. Our single-pulse approach enables 3D nanoprinting to transition from rapid prototyping to mass fabrication, critical for technology fields including metamaterials⁸, microrobotics⁹, inertial fusion energy^{10,11}, or drug delivery¹², in which many millions or billions of printed objects are needed.

Does physics impose a limit on the speed or rate at which we can manufacture three-dimensional (3D) objects? We argue that such a limit exists and that it is connected to the speed of light, the fundamental maximum speed at which information can be transmitted according to relativity. Yet, up to this point, 3D printing has been far from this limit.

Then, what is the metric of printing speed and where does the field currently stand? In 3D printing, 3D objects are decomposed into 3D volume elements called ‘voxels’ in analogy to the well-known two-dimensional (2D) picture element or ‘pixel’. In the simplest case of only a single constituent material, each voxel corresponds to one bit of information. Therefore, any manufacturing apparatus converts a digital representation of an object into physical reality. State-of-the-art 3D printers presently operate at peak print speeds or rates of about $10^8 \text{ voxel s}^{-1}$ (1–3,5,6). Consider that meaningfully sized objects require vast numbers of bits. For example, a single 1 cm side-length cube with $0.5 \mu\text{m}$ size cubic voxels already contains almost 10^{13} bits. At this rate, manufacturing said cube would take about 10^5 s, almost an entire day for a single object. Hence, mass fabrication has been out of reach.

Holography, which was introduced by Nobel laureate Dennis Gabor around 1948¹³, provides a route towards faster printing. Therein, the phase profile of a light wave can be shaped or programmed to deliver information via a targeted 3D light field by interacting with a 2D structure called a hologram. Such a hologram can be, for instance, a phase mask, a diffractive

optical element (DOE), a spatial light modulator, or an optical metasurface. This 3D light-intensity distribution can then be converted by a sufficiently transparent photosensitive material into a corresponding 3D distribution of photo-excited molecules, which translates into a 3D distribution of chemical bonds, forming a 3D distribution of voxels, and thus a targeted 3D object. Such holographic exposure of photosensitive media is not new and has been used in previous experiments^{14–21}.

The key contribution of our present work is that we push holographic exposure into the regime in which a *single* exposing light pulse is so short that the exposure process is limited by the finite speed of light c (inside of the photosensitive medium)²². The time of this holographic exposure is then defined by the time of flight $t = L/c$ it takes the light to propagate through the length L of the object (plus the negligibly short pulse duration) (Fig. 1a). Correspondingly, in the short-pulse exposure regime, the achievable voxel exposure rate is also proportional to the speed of light c . The actual value of this rate in units of voxel s^{-1} is additionally determined by the largest spatial cross-section of the targeted object and by the wavelength of light λ (inside of the photosensitive medium). The wavelength enters through the attainable resolution determined by Abbe’s formula. At the diffraction limit for 2π solid-angle illumination, the lateral resolution is $\lambda/2$, the axial resolution is λ – for one-photon absorption in the photosensitive medium as well as for multi-photon absorption²³. To be conservative, we set the lateral and axial voxel extent equal to the respective resolution, leading to a diffraction-limited (cubic) voxel volume of $\lambda^3/4$. A cube of size L and volume L^3 then contains $4(L/\lambda)^3$ voxels that are exposed in the time of flight $t = L/c$. Hence, the estimated light-speed-limited voxel exposure rate is $c \times \frac{4L^2}{\lambda^3}$ voxel s^{-1} (Fig. 1b). We have argued previously that the pulse energy required for a single-shot exposure is proportional to the object’s largest spatial cross-section and not the total object volume²². Such a relation would hold true for a photosensitive medium that is sufficiently transparent, as is the case for

73 multi-photon photoresists²². Furthermore, the pulse energy is inversely proportional to the
74 sensitivity of the medium²⁴, favoring multi-photon resists with high sensitivity figure of
75 merit²⁵.

76 To achieve this speed-of-light printing, we design holograms for targeted 3D objects; we
77 realize these holograms in the form of laser-printed DOEs; and we use these holograms to
78 expose a highly sensitive photoresist to define different complex-shaped 3D microstructures.

79 We exploit multi-photon absorption, using *single*, 35 fs duration, up to 20 μJ energy laser
80 pulses at around 800 nm free-space wavelength. We arrive at an exposure or print rate
81 exceeding 10^{19} voxel s^{-1} for $L \approx 100 \mu\text{m}$ and single laser pulses with center wavelength
82 $\lambda \approx 800 \text{ nm}/n$ (with refractive index $n \approx 1.5$ of the photosensitive medium). The achieved
83 peak value of 10^{19} voxel s^{-1} is eleven orders of magnitude larger than the current state-of-
84 the-art and brings 3D laser nanoprinting from rapid prototyping to the regime of mass
85 fabrication. We illustrate this possibility by printing complex-shaped 3D microparticles,
86 including some that have recently been considered for pharmaceutical applications¹². Finally,
87 we bring our results into a larger context and elaborate on the future prospects of 3D
88 holographic laser nanoprinting.

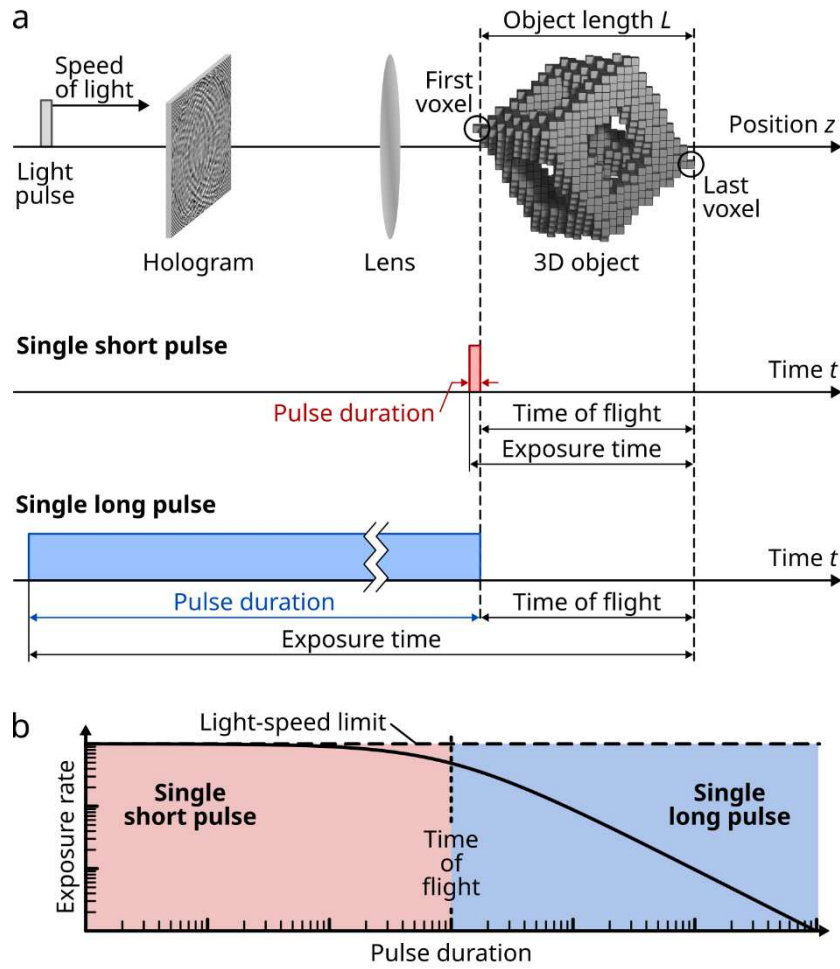


Fig. 1: Light-speed-limited exposure rate during single-pulse holographic 3D printing.

a, Schematic of a holographically printed cubic object. The two cases of a single short and single long light pulse for exposing the object are illustrated, comparing the pulse durations with the total object exposure time and time of flight of each pulse. **b**, Dependence of exposure rate, i.e., number of exposed voxels within the exposure time, on pulse duration. Regions in the plot are highlighted for the two cases of a short and a long light pulse. The exposure rate converges towards the light-speed limit for short pulse durations.

98 Hologram design and realization

99 The idea of holographic 3D printing is illustrated schematically in Fig. 2a and Supplementary
100 Video 1. A single, short laser pulse with a plane wave front impinges from below and passes
101 through a computer-generated hologram. The hologram imposes a spatially defined 2D phase
102 profile onto the pulse, such that a certain 3D light field results in the focal region of an oil-
103 immersion high-numerical-aperture microscope objective lens. This 3D light field exposes a
104 photosensitive medium (a photoresist) and a targeted 3D microstructure results after the
105 development process, which washes out the regions that are illuminated below a certain
106 threshold. For target 2D light fields, the Gerchberg-Saxton algorithm, an iterative Fourier-
107 transform algorithm,²⁶ is well established to solve the inverse problem of designing the
108 hologram. For 3D light fields, freely prescribing the intensity at each and every point in space
109 is fundamentally not possible. However, the threshold behavior of the photoresist allows us to
110 relax the problem. We use a generalized gradient-descent optimization approach^{27,28}, which is
111 based on maximizing a novel objective function f that accounts for the following three
112 aspects. (i) An iso-intensity surface (at the polymerization threshold) of the 3D light field
113 created by the hologram defines the surface of the 3D microstructure to be printed. Ideally, to
114 avoid inner porosity, the intensity is not below that iso-intensity at any point within this
115 surface. Therefore, any insufficient exposure within the volume of the targeted microstructure
116 reduces the value of the objective function f_{Solid} . (ii) The intensity *outside* of the 3D
117 microstructure is ideally zero to not induce any photoreactions there. While extended zero-
118 intensity regions of the 3D light field nearby high-intensity regions are clearly not possible,
119 we still penalize intensities close to the solidification (polymerization) threshold *outside* the
120 object through the objective function f_{Void} to obtain high exposure contrast between *inside*
121 and *outside*. To this end, N -photon absorption rather than one-photon absorption also helps by
122 effectively exposing the photosensitive medium with the N -th power of the intensity profile,

which suppresses polymerization in the tails of the intensity distribution. (iii) Lastly, the light intensity inside the volume defined by that iso-intensity surface could locally become much larger than that of the iso-intensity. Such undesired ‘hot spots’ can lead to micro-explosions damaging the printed structure rather than just inducing polymerization, particularly when using multi-photon absorption^{29,30}. Therefore, we penalize excessively large intensities *inside* the 3D microstructure through the objective function f_{Expl} . The resulting spatially defined objective value with respect to all three of these objective functions is depicted graphically in Fig. 2b. Further mathematical details of the hologram optimization procedure are given in the Methods.

Figure 2c illustrates the effect of each of the three discussed contributions to the objective function. Using three different figures of merit (FoMs, see Methods and Extended Data Fig. 1), we compare the resulting 3D light fields with an example target object: a 3D trefoil knot structure (Fig. 2a). The result with $f = f_{\text{Solid}}$ leaves substantial unwanted polymerization around the target (blue iso-intensity surfaces indicate polymerized regions). The choice $f = f_{\text{Solid}} + f_{\text{Void}}$ eliminates the extra polymerization but still leaves severe overexposed regions (magenta iso-intensity surfaces). The optimization utilizing the complete objective function $f = f_{\text{Solid}} + f_{\text{Void}} + f_{\text{Expl}}$ results in a hologram producing the most optimal structure. Clearly, however, the results are not always perfect, due to the occurrence of wavelength-scale speckles, which are well known in the context of holography³¹. We have found such speckles for many different targeted 3D microstructures. In the context of 3D printing, the speckles can be seen as voxel or bit errors; the mean speckle size indicates the minimum accessible voxel size. Some of the speckles lead to iso-surfaces that are disconnected from the main 3D microstructure and are not important as they are expected to be washed out in the development process. Other speckle contributions lead to a roughening of the 3D microstructure, i.e., to distortions with respect to its targeted shape and surface. For

applications in pharmacy requiring huge numbers of identical 3D microparticles³², these imperfections are likely not relevant. In other cases, e.g., for 3D printed free-form microlenses³³, such wavelength-scale deviations from smooth optical-grade surfaces are clearly not acceptable.

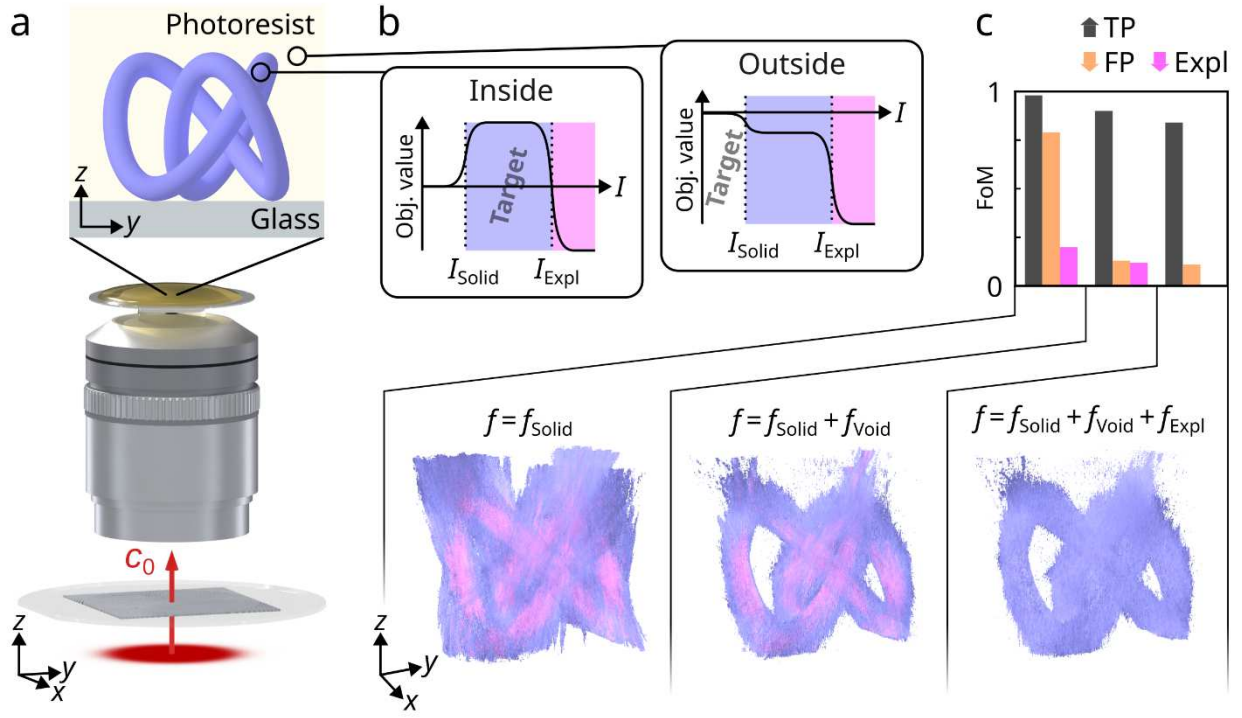


Fig. 2: Design of holograms for generating 3D light fields. **a**, Simplified schematic of a transmission hologram in combination with a microscope objective lens to optically generate a 3D light field. Inset shows a target trefoil knot structure within the objective lens focal volume. **b**, Graphical illustration of the optimization objective function value for the local light field intensity both inside and outside of the target structure volume during the hologram design. I_{Solid} and I_{Expl} are the threshold light intensities for solidification and micro-explosions. **c**, Separate 3D isometric views of calculated light intensity fields optimized considering different contributions to the objective function. The blue and magenta iso-intensity surfaces correspond to the solidification threshold and the micro-explosion

threshold, respectively. The histogram shows normalized figures of merit (FoMs) in comparison to the target structure. TP, true positive; FP, false positive; Expl, explosion.

We realize the designed holograms by two-photon-absorption 3D printed DOEs (Fig. 3). We have previously successfully realized similar DOEs³⁴ using commercially available technology (Nanoscribe, Quantum X) and, e.g., used them to holographically create 2D focus arrays for multi-focus, multi-photon 3D printing^{2,35}. A scanning electron micrograph (SEM) of the surface of a DOE used in this work is depicted in Fig. 3c. Notably, these DOEs do not have dead areas which are common for dynamic spatial light modulators. Such dead areas contribute to the zeroth order of the hologram, leading to a detrimental, single, sharp focus inside the targeted 3D microstructure that is particularly undesirable for multi-photon absorption³⁶. Furthermore, these DOEs have a much higher spatial resolution than common spatial light modulators, potentially leading to a better quality and larger information content of the 3D printed microstructure. These polymer-based DOEs have proven to withstand long-term illumination with high laser powers from femtosecond laser oscillators². Here, however, the mean laser powers are very low and it is rather the high pulse energy that might lead to sample deterioration. Still, we have not noticed any degradation effects for any of the DOEs used in the experiments reported below.

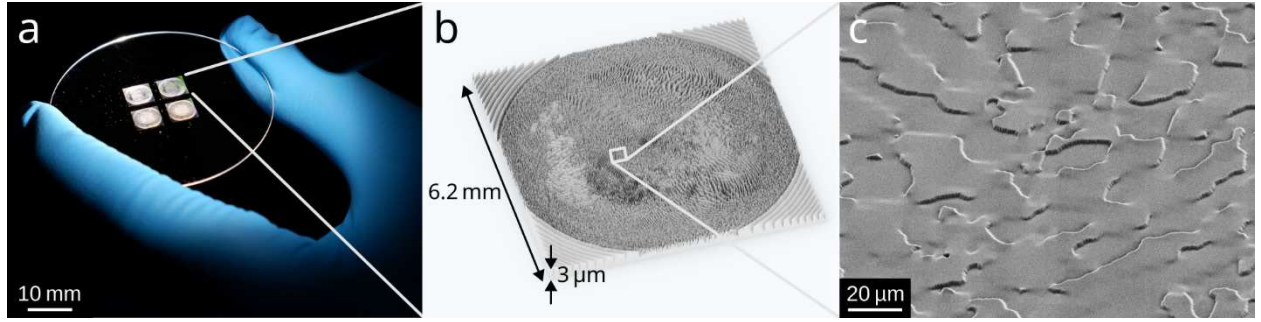


Fig. 3: Fabricated hologram as DOE. **a**, Optical photograph of four printed DOEs on a glass wafer. **b**, Exaggerated-height rendering of experimentally measured topographical height profile of a DOE. **c**, SEM of a magnified region of the printed DOE.

Holographic printing with a single, femtosecond pulse

The fabricated holograms are imaged with 1:1 magnification to the back focal plane of the microscope objective lens, whose front focal volume is positioned above a glass substrate and inside a photoresist. The acrylic photoresist used is based on the initiator BBK (see Methods) which exhibits the largest known sensitivity figure of merit for multi-photon absorption (6), and therefore reduces the required optical-pulse energy. A mechanical stage repositions the substrate after each print but is completely stationary during the printing of each structure. The optical setup is shown in Extended Data Fig. 2 and described in the Methods.

The gallery of oblique-view electron micrographs shown in Fig. 4 provides examples of different, holographically printed 3D microparticles – each one exposed by only a single 35 fs laser pulse. The printed particles in Fig. 4a-e are exposed using holograms designed by the optimization algorithm described above within overall volumes of $10^3 - 10^6 \mu\text{m}^3$. The solid volume of material of the design structures is between $10^2 - 10^5 \mu\text{m}^3$, see Extended Data Table 1. The examples in Fig. 4a-d are ordered according to their largest spatial cross-section. A separate hologram is designed and fabricated to print each different 3D particle, while all

holograms enable generation of highly reproducible 3D light fields and correspondingly 3D printed particles identical to each other (Fig. 4e). Notably, any effect of the pulse-to-pulse stability of the laser system ($< 1.3\%$ standard deviation in pulse energy, see Extended Data Fig. 3) is negligible between consecutively printed structures.

Through the calculated red-color surfaces in Fig. 4e, we represent the boundaries of total energy deposition within the photoresist at the polymerization threshold, termed an iso-dose surface. These iso-dose surfaces are obtained from calculations of the light field resulting from a broadband laser pulse incident on the hologram using Fourier optics and assuming two-photon absorption, see Methods. Regions of above-threshold dose unconnected from the main structure surface are not illustrated as those pieces of solidified material are expected to be washed out during development. The iso-dose surfaces (Extended Data Table 2) resulting from the optimized holograms show imperfections relative to the initial target, such as surface roughness and excessive or missing regions of dose, due to the speckle previously mentioned. The as-printed structures match the calculated iso-dose surfaces well, capturing the overall shape as well as the speckle contributions, e.g., the protrusions at the top of the trefoil knot in Fig. 4a.

Beyond the light-field distribution, chemical effects including the diffusion of radicals and quenchers, e.g., oxygen, are known to play a strong role during 3D printing³⁷. We have therefore represented this diffusion in Fig. 4e (blue colored) by additionally convolving the calculated dose distribution with a sphere with Gaussian fall-off to $1/e$ at radius $1\text{ }\mu\text{m}$ (a reasonable diffusion length³⁸ within polymerization timescales) before thresholding. This results in smoother iso-dose surfaces, even better matching the as-printed structure surfaces. However, we observe some excessive polymerization beyond that of the calculated iso-dose surfaces nearer the glass substrate such as the strings of polymer connecting the substrate to the lower left spike of the pharmacone³² in Fig. 4b. We attribute this excess polymerization to

225 reduced in-diffusion of chemical quenchers close to the glass interface, which is not captured
226 by our basic diffusion model. Overall shrinkage of the printed structures is also apparent in
227 comparison to the true-to-scale calculated iso-dose surfaces.

228 We explore the achievable voxel size of this holographic printing using the microparticle
229 shown in Fig. 4f. It is exposed using a hologram imparting a filtered random distribution of 0
230 to 2π phase onto the laser pulse. This structure epitomizes the effect of the speckle and the
231 observed features are reasonably close in size to the theoretically estimated average voxel
232 size³⁵ of the holographic printing of 400 nm (267 nm lateral, 533 nm vertical).

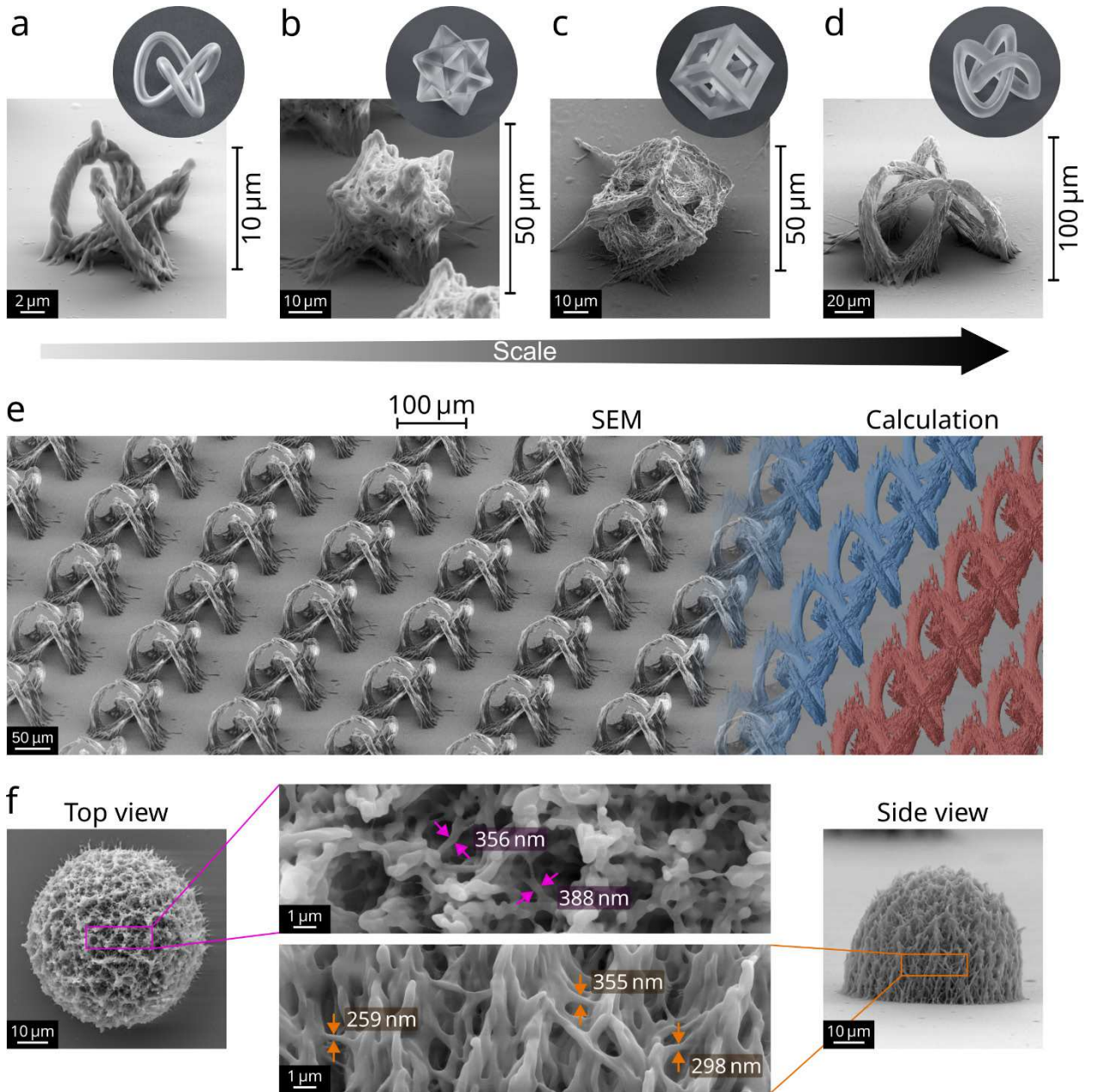


Fig. 4: 3D microstructures printed at the speed of light. Gallery of individual 3D printed microparticles each printed with a single, femtosecond laser pulse: **a**, trefoil knot $L = 9.7 \mu\text{m}$, **b**, pharmacone $L = 52 \mu\text{m}$, **c**, hollow cage $L = 72 \mu\text{m}$, **d**, trefoil knot $L = 97 \mu\text{m}$. Axial length L refers to the respective design structures shown in insets. **e**, Array of trefoil knot microparticles, each printed under nominally identical conditions, alongside an array of iso-dose surfaces from the computationally designed 3D light fields (red), which were convolved with a 3D Gaussian with $1/e$ -radius of $1 \mu\text{m}$ (blue). **f**, Result of randomized phase hologram

and measured size of typical features in lateral (pink) and axial direction (orange). Brightness of SEMs in c and e has been adjusted nonlinearly for improved visibility.

Scalability and the potential of holographic 3D printing

As noted, the required laser pulse energy should scale linearly with the cross-sectional area for holographic 3D printing with a single light pulse. This naively assumes that light can be arbitrarily redistributed in each layer throughout the entire propagation volume. We illustrate this scaling with the dashed line in Fig. 5a, which begins from the threshold pulse energy required to print a single voxel²², see Methods. We then calculate the physical 3D light field using scalar diffraction theory and the corresponding 3D dose distribution for five different objects (the same as in Fig. 4 and Extended Data Tables 1 and 2). The calculated pulse energy required to achieve the threshold dose is plotted against the largest cross-sectional area within each target object (empty white markers). These pulse energies roughly follow the trendline, though they exhibit a slightly lower slope. The experimentally determined pulse energies to holographically print the same objects (solid black markers) agree very well. Notably, different objects with similar cross-sectional areas can require slightly different pulse energies due to the distribution of the pulse energy in space while propagating to form each physically realizable 3D light field. From our results, it is clear that current femtosecond laser oscillators, suitable for traditional non-holographic multi-photon printing³⁹, lack the pulse energy to achieve single-pulse printing beyond a few $10\ \mu\text{m}^2$. In contrast, amplified femtosecond laser systems, like the one used in this work, can readily provide pulse energies of a few mJ. Energetically, millimeter-scale objects, such as inertial fusion targets^{10,11}, are then within reach. The remaining challenges for further upscaling lie in overcoming current optical and computational limits.

265 In Fig. 5b we compare our work to the peak printing rates of other recent and well-
266 established light-based 3D printing technologies (see Extended Data Fig. 4 for details and
267 references). The peak print rates for other techniques reach about 10^8 voxel s^{-1} . For our
268 largest structure we achieve a peak print rate of 1.2×10^{19} voxel s^{-1} – eleven orders of
269 magnitude higher than other methods. Of course, 3D printers usually maintain their peak rate
270 only for finite times during a print job. For this work, the repetition rate of the laser of 1 kHz
271 would allow to print 1,000 structures per second. This limits the *mean* print rate to
272 6×10^9 voxel s^{-1} , which is still $50\times$ faster than the *peak* print rate of existing technologies.
273 Previous routes to increasing 3D printing speed have primarily focused on more foci^{2,3} and
274 faster scanning^{2,40} of light through the resist where the scanning is limited by the exposure-
275 pulse duration. Now, 3D printing has reached the speed-of-light limit by exposing an entire
276 3D structure with a single, femtosecond pulse. Therefore, we foresee that future increases in
277 the peak print rate will instead rely on printing larger objects, while increasing the mean print
278 rate can also be achieved by moving towards higher repetition rate lasers. In this way, 10 kHz
279 or 100 kHz laser systems with high peak powers would enable printing 10,000 or 100,000
280 structures per second independent of their size, pushing mass production of tailored
281 microparticles into previously unattainable regimes.

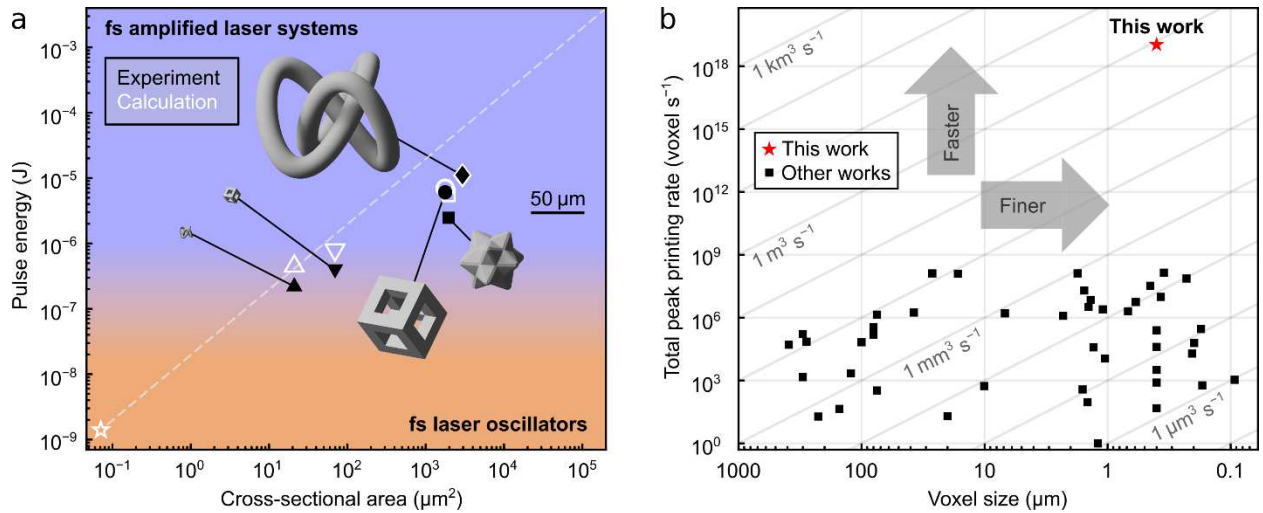


Fig. 5: Energy scaling and printing rate of holographic 3D printing. **a**, Experimental (solid black markers) and calculated (empty white markers) laser pulse energies for printing the indicated target 3D structures plotted against their largest cross-sectional areas. The calculated energies result from computing and visualizing 3D dose distributions using the threshold dose required for a single voxel (star point). The dashed trendline represents a linear scaling. **b**, Peak printing rates of 3D printing technologies versus their average minimum voxel size. See Extended Data Fig. 4 for a more detailed version of Fig. 5b with references.

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Methods

Computational methods

The propagation of light through the optical setup is modeled using the angular-spectrum method and the principles of Fourier optics⁴¹. Let $E_0(x, y, f)$ be the electric field of the input beam at the back focal plane of the objective lens (and at frequency f), before the hologram. The field after the hologram is calculated using the thin-element approximation $E_1(x, y, f) = E_0(x, y, f) \exp[i\phi(x, y, f)]$, where $\phi(x, y, f) = 2\pi f(n - 1)h(x, y)/c_0$ is the transmission phase, calculated from the surface height $h(x, y)$ and refractive index of the hologram material n ; c_0 is the speed of light in vacuum. For later convenience we parameterize the surface in terms of the transmission phase at some central frequency f_0 , in which case $\phi(x, y, f) = \phi(x, y, f_0)f/f_0$ as long as the frequency dependence of n is negligible. The field $E_1(x, y, f)$ is transferred to the front focal plane of the objective lens using the Fourier-transform property

$$E_2(x, y, f) = \mathcal{F}[E_1]\left(f_x = \frac{xf}{c_0F}, f_y = \frac{yf}{c_0F}\right), \quad (1)$$

where $\mathcal{F}$ denotes the Fourier transformation that is evaluated at the specified spatial frequencies f_x and f_y , and F is the effective focal length of the objective lens. This focal-plane field is then propagated to the region around the focal plane by the angular spectrum method

$$E(x, y, z, f) = \mathcal{F}^{-1}\{\mathcal{F}[E_2](f_x, f_y) \exp(ik_z z)\}, \quad (2)$$

417 where $k_z = 2\pi \sqrt{(fn_{\text{Mono}}/c_0)^2 - f_x^2 - f_y^2}$, with n_{Mono} being the refractive index of the
 418 monomer. To make sure that the objective lens's numerical aperture of 1.4 is obeyed, the
 419 amplitudes of all waves with $\sqrt{f_x^2 + f_y^2} \geq 1.4f/c_0$ are set to zero in the angular spectrum
 420 $\mathcal{F}[E_2]$. We can then calculate the frequency-averaged intensity in the focal region

$$421 \quad I(x, y, z) = \sum_j w_j |E(x, y, z, f_j)|^2, \quad (3)$$

422 where the frequency weights w_j are taken from the spectrum of the laser. For the purposes of
 423 optimization, we assume a simple polymerization model: where $I(x, y, z)$ exceeds the
 424 polymerization threshold I_{Thr} the monomer polymerizes fully. This is an approximation
 425 because $I(x, y, z)$ is only a frequency-domain average and ignores the time-domain behavior
 426 of the pulse. However, the approximation significantly reduces the computational effort,
 427 mainly because only a few frequencies are needed to represent the laser's spectrum, while a
 428 time-domain simulation of the pulse would require many more to accurately compute the
 429 instantaneous pulse intensity by the inverse Fourier transformation of $E(x, y, z, f)$.

430 As explained in the main text, there are three conditions that the optimized intensity
 431 distribution should fulfill: (i) the intensity should exceed the polymerization threshold inside
 432 the target object, (ii) it should not exceed the polymerization threshold outside the target, and
 433 (iii) it should not exceed the threshold for micro-explosions. These conditions correspond to
 434 the three terms of the objective function $f = f_{\text{Solid}} + f_{\text{Void}} + f_{\text{Expl}}$, which is to be maximized
 435 with respect to the hologram's transmission phase $\phi(x, y, f_0)$. To model the threshold
 436 behavior in a differentiable manner, we define a smooth step function $S(x) = 1/[1 +$
 437 $\exp(-x)]$. We also define the target object as an indicator function $T(x, y, z)$ which is equal
 438 to 1 inside and 0 outside the target object. Furthermore, we define a beam dump region
 439 (where the 'void' penalization does not apply) using another indicator function $B(x, y, z)$,

allowing excess intensity to be directed preferentially away from the target structure. The objective function terms are then defined as integrals of the objective values:

$$f_{\text{Solid}} = \iiint S \left[\frac{I(x, y, z) - I_{\text{Thr}}}{\Delta I} \right] T(x, y, z) \, dx dy dz \quad (4)$$

$$f_{\text{Void}} = -C_{\text{Void}} \iiint S \left[\frac{I(x, y, z) - I_{\text{Thr}}}{\Delta I} \right] [1 - T(x, y, z) - B(x, y, z)] \, dx dy dz \quad (5)$$

$$f_{\text{Expl}} = -C_{\text{Expl}} \iiint S \left[\frac{I(x, y, z) - I_{\text{Expl}}}{\Delta I} \right] T(x, y, z) \, dx dy dz. \quad (6)$$

Here, C_{Void} and C_{Expl} are the penalty weights for the void and explosion parts, ΔI is the width of the step, and $I_{\text{Expl}} = 3I_{\text{Thr}}$ is the micro-explosion threshold. The quantities C_{Void} , C_{Expl} , ΔI , and I_{Thr} are considered to be ‘hyperparameters’ to be separately optimized, and allow tradeoffs to be made. For instance, a low C_{Void} generally leads to a more solid structure which has extra polymerization around it, while a high C_{Void} avoids this extra polymerization but yields a more porous structure due to the restrictions it imposes on the intensity distribution.

We implement the optical simulation and optimization procedures using the `jax` Python package^{42,43} that allows automatic differentiation of the code and thus fast calculation of the gradient of the objective function. The transmission phase of the hologram is parameterized by defining a regular grid and letting $\phi(x, y, f_0)$ at each grid point (m, n) be an independent parameter, $\phi(x_m, y_n, f_0)$. The objective function is then maximized with respect to all these parameters using the Adam algorithm⁴⁴. In addition to the grid on the hologram at the back focal plane, we also discretize the front focal plane and its surroundings using a 3D grid. The integrals in Eqs. (4–6) are then evaluated as Riemann sums. A complication in Eq. (1) is that the coordinates at which it is evaluated depend on the frequency f . To overcome this issue, we fix a reference computational grid at the central frequency of the laser, and thereafter use the same computational grid for all frequencies on the front focal plane. At the back focal

462 plane, fields are interpolated from the reference grid [where $\phi(x_m, y_n, f_0)$ are also defined] to
 463 the grid needed by a particular frequency by using the
 464 `jax.image.scale_and_translate` function with the `lanczos3` method and no
 465 anti-aliasing.

466 To exemplify the choice of parameters, in the following we provide the parameters used to
 467 optimize the 100 μm trefoil knot. The parameters for the other structures can be found in the
 468 code provided in a separate file. Central wavelength $\lambda_0 = 0.8 \mu\text{m}$; frequency weights $w_j =$
 469 $\exp[-2 \left(f_j - \frac{c_0}{\lambda_0}\right)^2 / \Delta f^2]$ with 5 equidistant frequencies f_j between $0.9715 c_0/\lambda_0$ and
 470 $1.0285 c_0/\lambda_0$, and $1/e^2$ spectral width $\Delta f = 10.7 \text{ THz}$; $F = 2 \text{ mm}$; $n_{\text{Mono}} = 1.48$; the reference
 471 back focal plane computational domain $x, y \in [-1.1 R_h, 1.1 R_h]$ with $R_h = 2.812 \text{ mm}$ and
 472 1,401 grid points along each dimension; front focal plane computational domain derived from
 473 this using the Fourier transform relationship is $248 \mu\text{m}$ wide; z -grid with $z \in [z_{\text{Sub}}, z_{\text{Max}}]$
 474 where z_{Sub} is determined automatically as the minimum z -coordinate of the target and $z_{\text{Max}} =$
 475 $70 \mu\text{m}$, with $z = 0$ defined as the geometric center of the trefoil knot; input beam $E_0(x, y) =$
 476 $1/[1 + \exp((r - R_h)/\Delta r)]$ where $r = \sqrt{x^2 + y^2}$ and $\Delta r = 0.02 R_h$; Adam optimizer
 477 parameters $\alpha = 0.3$, $\beta_1 = 0.9$, $\beta_2 = 0.999$, number of iterations 800; hyperparameters C_{Void}
 478 $= 0.8$, $C_{\text{Expl}} = 4.0$, $\Delta I = 0.0875 I_{\text{Thr}}$, and $I_{\text{Thr}} = 0.25 \times P_{\text{In}}/A_{\text{xs}}$, where P_{In} is the power of the
 479 input beam and A_{xs} is the maximum cross-sectional area of the target object in one of the xy -
 480 planes. We found the hyperparameter values by brute-force search (see the subsection
 481 below). The beam dump region [defined by $B(x, y, z)$] was chosen to be a hollow cylinder
 482 around the target object with inner radius $55.8 \mu\text{m}$ and outer radius $74.4 \mu\text{m}$. The initial guess
 483 for the optimizer was $\phi(x, y, f_0) = -(2\pi)/\lambda_0 \times r^2/(2r_{\text{Init}})$ with $r_{\text{Init}} = 500 \text{ mm}$.

484 In post-optimization calculations (Fig. 4e and Extended Data Table 2) we dispense with the
 485 frequency-domain average intensity and calculate the two-photon absorption dose, defined as

$$D(x, y, z) = \int |\tilde{E}(x, y, z, t)|^4 dt, \quad (7)$$

where the time-domain electric field $\tilde{E}$ is calculated as the inverse Fourier transform of the frequency-domain field E :

$$\tilde{E}(x, y, z, t) = \int E(x, y, z, f) \exp(i2\pi ft) df. \quad (8)$$

In this calculation, we assume that only a small fraction of the pulse energy is absorbed and thus do not take this loss into account. We consider 51 equidistant frequencies between $0.933 c_0/\lambda_0$ and $1.066 c_0/\lambda_0$ to calculate the time-domain electric field, corresponding to laser pulses recurring every 1 ps (i.e., spaced out by 200 μm). The corresponding intensity distributions are visualized in Supplementary Video 1. The total deposited dose is calculated from 51 time steps throughout the repetition time of 1 ps following Eq. (7). We calculate the threshold dose value by first scaling the threshold pulse energy used to polymerize one voxel in ²⁵ by $\sqrt{50}$ to obtain the energy to print that voxel with one pulse. The threshold dose value is then obtained from time-integrating a Gaussian-shaped pulse of pulse energy 1.724 nJ and pulse duration 140 fs. We note that these values are for a photoresist consisting of 0.5 wt. % BBK in PETA. As we use a concentration of 0.8 wt. % BBK in this work, the calculated pulse energies in Fig. 5a may be overestimated. The pulse energies in Fig. 5a and Extended Data Tables 1 and 2 are chosen such that the calculated iso-dose surfaces visually match the reference structures. The image resolution of the iso-dose surfaces of the two smaller objects in Extended Data Table 2 is increased by zero-padding the holograms to increase the size of the grid.

Figures of merit

The three figures of merit shown in Fig. 2c of the main text are defined as follows: true positive (TP) is the fraction of the target object's volume that is polymerized (where

$I(x, y, z) \geq I_{\text{Thr}}$; false positive (FP) is the volume of polymerized material outside the target divided by the volume of the target; and explosion (Expl) is the fraction of the target object's volume where the accumulated dose exceeds the micro-explosion threshold. The explosion threshold is approximated to be 3 times the polymerization threshold. Ideally, TP is equal to 1 while FP and Expl are equal to 0. Note that these figures of merit essentially correspond to the three parts of the objective function [Eqs. (4–6)].

Hyperparameter optimization

The hyperparameters C_{Void} , C_{Expl} , ΔI , and I_{Thr} are separately optimized by brute-force search by running the optimization for each hyperparameter case, evaluating the true positive, false positive, and explosion figures of merit (as in Fig. 2), and picking one of the results for experimental realization. Typically, setting $\Delta I = 0.0875 I_{\text{Thr}}$ and $C_{\text{Expl}} = 4$ are reasonable choices, leaving C_{Void} and I_{Thr} as the main two hyperparameters to optimize.

Extended Data Fig. 1 shows an example for the 100 μm trefoil knot where we vary C_{Void} and I_{Thr} and calculate the true and false positive figures of merit (TP and FP). Clearly, decreasing C_{Void} increases both TP and FP, indicating a more solid structure but with extra polymerization around it. Meanwhile, decreasing I_{Thr} improves the TP figure of merit while making FP slightly worse. The case with $I_{\text{Thr}}A_{\text{xs}}/P_{\text{In}} = 0.25$ and $C_{\text{Void}} = 0.8$ has a reasonable balance between TP and FP and was chosen for experimental realization.

Computational hardware, speed, and system size limitations

We performed all optimization runs on graphics processing units (Nvidia A100) using 32-bit floating point numbers. In the example of the 100 μm trefoil knots, each run took approximately 7 minutes, although the total computation time was substantially longer due to the many runs required for hyperparameter optimization.

532 We were limited to approximately 100 μm target objects due to memory limitations: just
 533 keeping the fields in memory takes up approximately 6 gigabytes in the 100 μm trefoil knot's
 534 case (a $1,401 \times 1,401 \times 75 \times 5$ array of complex numbers) and there are other arrays that take up
 535 more memory. However, this is not a fundamental limitation: the algorithm could be changed
 536 to sweep through the volume of the object along z rather than calculating the entire 3D field
 537 distribution at once. This will allow larger objects to be created (while maintaining the
 538 necessary grid resolution) using the same hardware.

539 **Target definitions**

540 Trefoil knots

541 We defined trefoil knot structure targets by taking the spine curve

$$542 \quad x = (s_{\text{Knot}}/5)[\sin(t) + 2 \sin(2t)],$$

$$543 \quad y = (s_{\text{Knot}}/5)[\cos(t) - 2 \cos(2t)],$$

$$544 \quad z = -2(s_{\text{Knot}}/5) \sin(3t),$$

545 where $t \in [0, 2\pi]$ and s_{Knot} sets the overall size of the knot (it is, approximately, the width of
 546 the spine curve along the x and y directions). The spine curve is convolved with a sphere of
 547 radius r_{Conv} to create a 3D object. For the two trefoil knots discussed in the article, $s_{\text{Knot}} =$
 548 10 μm and $s_{\text{Knot}} = 100 \mu\text{m}$, and $r_{\text{Conv}} = 0.08 s_{\text{Knot}}$. In the 100 μm case, the convolving
 549 object was a cylinder (of radius r_{Conv} and height $2r_{\text{Conv}}$) instead of a sphere.

550 Cages

551 The cage targets were defined by taking a cube of side length s_{Cage} and carving out everything
 552 except the edges. The width of the edges is $s_{\text{Cage}}/4$. The cage is rotated by 45° about the y -
 553 axis so that it stands on one of its edges, as this improved the quality of the structure when
 554 compared with a cage lying flat on the substrate.

555 Random-phase particle

556 The random-phase particle is simply the result of a correlated-noise phase mask. To define
557 the phase mask we took uniformly-distributed two-dimensional white noise with 2π
558 amplitude, filtered it using a Gaussian kernel (of shape $\exp[-(x^2 + y^2)/w^2]$ with $w =$
559 $25\text{ }\mu\text{m}$), and re-scaled the result such that the difference between the maximum and
560 minimum value was again 2π .

561 Pharmacone

562 The pharmacone structure was defined in an STL file which was discretized onto a 3D grid
563 using the Python library `stl-to-voxel`⁴⁵.

564 **Photoresist and chemicals**

565 The photoresist consists of 0.8 wt. % (2E,6E)-2,6-Bis(4-(dibutylamino)benzylidene)-4-
566 methylcyclohexanone (BBK) in pentaerythritol triacrylate (PETA, Sigma-Aldrich). BBK is
567 synthesized as reported previously²⁵. All other chemicals are used as received. The
568 photoresist is made by adding BBK to PETA and using an orbital shaker to mix the resist at
569 $40\text{ }^{\circ}\text{C}$ for 100 hours.

570 **Printed diffractive optical elements (DOEs)**

571 The DOEs are fabricated using a Nanoscribe Quantum X lithography system in 2GL mode
572 using Nanoscribe IP-S photoresist and a $25\times$ objective lens (Zeiss LCI Plan-Neofluar $25\times/0.8$
573 Imm Corr DIC). A constant offset in-between $1.5\text{ }\mu\text{m}$ and $4\text{ }\mu\text{m}$ is added to the DOE height
574 maps, which are available in the data repository as 16-bit grayscale images. These grayscale
575 images are imported into the software GrayScribeX with pixel size 400 nm . Slicing is set to
576 $1\text{ }\mu\text{m}$ and hatching to 200 nm , the interface is offset to $-1.5\text{ }\mu\text{m}$ and the laser is scanned at a
577 speed of 200 mm s^{-1} . The size of the square print fields is set to $420\text{ }\mu\text{m}$, neighboring print

fields overlap by 60 μm and are stitched by 2GL stitching. Substrate tilt and curvature are measured and compensated by the software automatically. After exposure, the samples are developed by immersing them into propylene glycol methyl ether acetate (PGMEA) twice for 10 minutes each, then into isopropyl alcohol (IPA) twice for 5 minutes each. Afterwards, they are blown dry with nitrogen.

The topography of the printed DOEs is measured using a Mahr MarSurf CM explorer spinning-disk confocal microscope with a 50 $\times$ / NA=0.95 objective lens, yielding height maps of 267 nm pixel size (see a rendering in Fig. 3b). The software Quandalf^{34,46} is used to compare the topography of a printed DOE to its calculated design and to generate pre-compensated height maps that account for systematic deviations which occur during printing. Each DOE used for holographic printing was pre-compensated based on two nominally identical printed DOEs, employing one cycle of the iterative algorithm.

3D holographic printing system

The experimental setup for 3D holographic printing is shown in Extended Data Fig. 2. We use a Spectra-Physics Solstice Ace ultrafast amplifier capable of emitting laser pulses at 1 kHz repetition rate, 800 nm center wavelength, 7 W average power, 35 fs FWHM pulse width and linear horizontal (with respect to the optical table) polarization. During printing, the laser is operated in the ‘Gated’ mode, allowing selective individual-pulse output. A periscope (not shown) rotates the laser polarization into the vertical direction. Before the printing setup, the laser pulses are attenuated by a fixed factor using beamsplitters in reflection (Newport 10Q08-03UF.BS90 and Eksma Optics 042-7750P, not shown). An uncoated wedged beamsplitter at Brewster’s angle filters remaining horizontally polarized components of the pulse. A variable attenuation stage consisting of a half-wave plate on a motorized rotation stage, in conjunction with a second identical wedged beamsplitter at

Brewster's angle, sets the pulse energy to a desired value. After demagnification by a lens pair ($f_1 = 300$ mm, Thorlabs LA1484-B; $f_2 = -200$ mm, Newport KPC028AR.16), an AdlOptica π Shaper 6_6_TiS converts the laser pulse's Gaussian spatial intensity profile into a flat-top profile. A prefabricated DOE is positioned close after the π Shaper. A 1:1-magnification lens pair ($f_3 = f_4 = 150$ mm, Thorlabs LA1417-B) relays an image of the DOE to the back focal plane of a microscope objective lens (Leica HC PL APO 100x/1.40 OIL CS2) which converts the holographically-shaped laser pulse into a 3D light field in the objective lens focal volume. The objective lens is focused, using immersion oil, through a cleaned borosilicate cover glass of thickness $170\text{ }\mu\text{m}$ (Marienfeld 0117580, 18 mm diameter) and into a drop of photoresist. The substrate is mounted into a custom fabricated holder and relocated in-between light exposures in three dimensions by a stack of two piezo stages (PI M-686.D64 and PI P-563.3CD, not shown).

A separate beam path allows for in-situ monitoring and interface finding during the printing process and is combined with the printing beam path beneath the objective lens by an ultrafast mirror (Newport 10B20UF.25) which acts as a short-pass dichroic mirror (~ 700 nm cut-off wavelength). For monitoring, the sample is illuminated by a red light-emitting diode (LED) above from above and imaged in transmission mode with the same microscope objective lens, in combination with an $f_5 = 100$ mm lens (Thorlabs LA1509-A) onto the sensor of a camera (Teledyne FLIR Blackfly BFS-U3-50S4M-C). Residual intensity of the printing pulse is blocked by a short-pass optical filter (Newport 10SWF-750-B, 750 nm cut-off wavelength) in front of the camera. For interface finding, a beam of 675 nm wavelength emitted by a laser diode (Thorlabs LPS-PM675-FC) is coupled into the imaging beam path using a long-pass dichroic mirror (Thorlabs DMLP638, 638 nm cut-on wavelength). The reflection at the interface between glass substrate and photoresist is observed in the camera.

626 During printing, output of the laser pulses from the ultrafast amplifier is triggered by a
627 computer which also controls movement of the stages. Everything is controlled via custom-
628 written LabVIEW software and data acquisition hardware (NI PCIe-6351, NI PICE-6353). In
629 this way, predefined scripts are used to automatically print structures at desired positions and
630 pulse energy.

631 **Pulse energy**

632 A cover glass placed in the beam path after the attenuation stage redirects a small part of the
633 laser beam onto a fast Si photodiode (Thorlabs DET10A2, not shown). The output signal
634 from the diode for each laser pulse used to print a 3D structure is measured using an
635 oscilloscope (Siglent SDS5034X). The corresponding pulse energy used for printing is
636 derived from a calibration of the photo diode signal against the average power measured by a
637 thermopile power meter (SLT LP10) placed in the beam path just before the π Shaper while
638 the laser is operating in the ‘continuous-fire’ mode (1 kHz). We then correct the quoted pulse
639 energies for optical losses further in the beam path (i.e., from the π Shaper, DOE, objective
640 lens, etc.) by measuring the optical power through a 5.6 mm diameter aperture in place of the
641 objective lens. Additionally, we further account for a transmission of the objective lens of
642 90 %, as given by the manufacturer at a wavelength of 800 nm. In this way, we find the
643 following total transmission of the beam path after our standard power measurement position
644 for each DOE (no DOE: 70.3 %, trefoil knot (10 μ m): 60.8 %, cage (10 μ m): 58.7 %,
645 pharmacone (50 μ m): 61.7 %, cage (50 μ m): 56.9 %, trefoil knot (100 μ m): 57.0 %,
646 correlated-noise hologram: 63.4 %). To optimize the laser pulse width in the focal volume of
647 the objective lens, the internal grating compressor of the ultrafast amplifier is tuned such that
648 the two-photon fluorescence intensity of a dye (Rhodamine 6G) applied onto the sample
649 substrate instead of a photoresist is maximized. The intensity is observed using the

monitoring camera. Initial experiments, including the pharmacone in Fig. 4b, used a gallium phosphide (GaP) photodiode to provide the signal for optimizing the pulse width.

Sample preparation and development

The 18 mm diameter glass coverslips used for substrates are first cleaned via sequential sonication at 60 °C in aqueous solutions of 4 vol. % Deconex OP 146, 2 vol. % Deconex OP 12PA-x, and 2 vol. % Deconex OP 171, with a cleaning in ultrapure water after each solution. All sonication steps are for 10 minutes. After blow drying with compressed nitrogen, the substrates are oxygen plasma-cleaned (Diener electronic Atto B) for 10 minutes. The plasma-treated substrates are then immersed in a solution of 0.2 vol. % of 3-Aminopropyltriethoxysilane in toluene under inert atmosphere for 1 hour before being rinsed with toluene and dried with nitrogen. After printing, samples are developed by immersing them into isopropyl alcohol (IPA) twice for 8 minutes each and a third time for 1 minute. Then, they are allowed to dry in air inside a fume hood.

Sample characterization

For imaging with scanning electron microscopy, a thin layer of Au (~10 nm) is sputtered on top of each sample. Imaging is performed with a Zeiss Leo 1530 scanning-electron microscope operated at 5 or 10 keV electron energy. Fiji software^{47,48} is used to measure the dimensions of features in the obtained images.

Data availability

The datasets generated during the current study are available in the RADAR4KIT repository⁴⁹, <https://doi.org/10.35097/t2wphpqdxgrq0hca>.
(Temporary link for review:
<https://radar.kit.edu/radar/en/dataset/t2wphpqdxgrq0hca?token=TGZSfiBSxrvLUruRUNkK>)

Code availability

The code generated during the current study is available in the RADAR4KIT repository⁴⁹, <https://doi.org/10.35097/t2wphpqdxgrq0hca>.
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770 **Author contributions**

771 S.K. and P.S. built the experimental setup and performed printing; S.K., J.S. and P.S.
772 acquired SEMs; M.N. wrote the code for hologram optimization and calculated the
773 holograms; S.K. fabricated the holograms and calculated the iso-dose surfaces; M.W. and
774 P.S. conceptualized the printing technique; M.L.M., C.R. and M.W. acquired funding;
775 M.L.M., C.R., M.W. and P.S. supervised the project; S.K., M.W. and P.S. drafted the original
776 manuscript; all authors contributed in reviewing and editing the paper.

777 **Competing interest declaration**

778 The authors declare no competing interests.

779 **Additional information**

780 **Supplementary information**

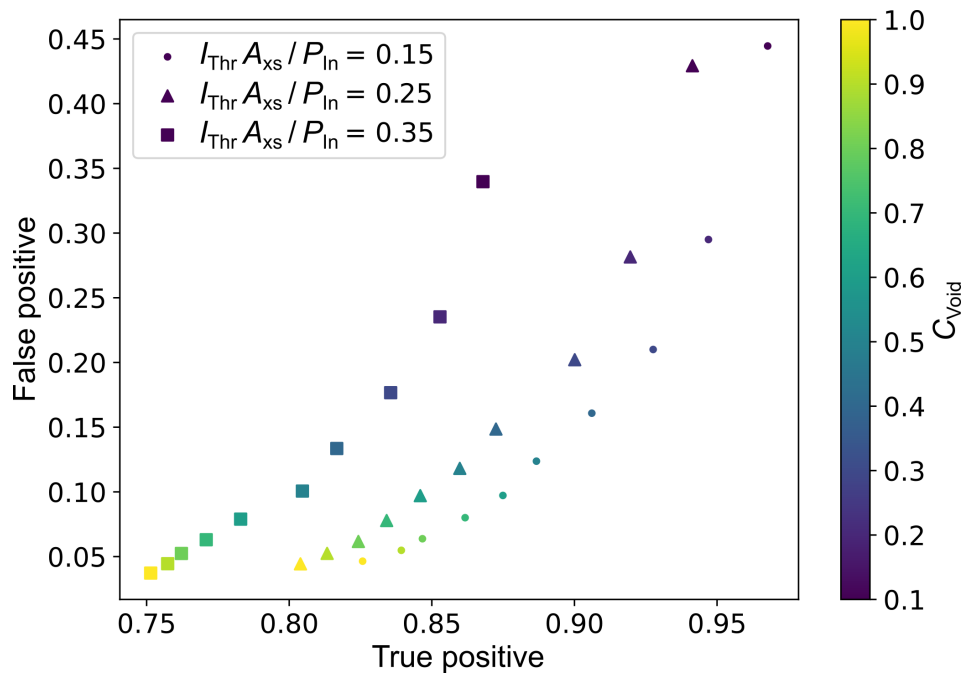
781 Supplementary Information is available for this paper.

782 **Corresponding author**

783 Correspondence and requests for materials should be addressed to Paul Somers
784 (paul.somers@kit.edu) or Martin Wegener (martin.wegener@kit.edu).

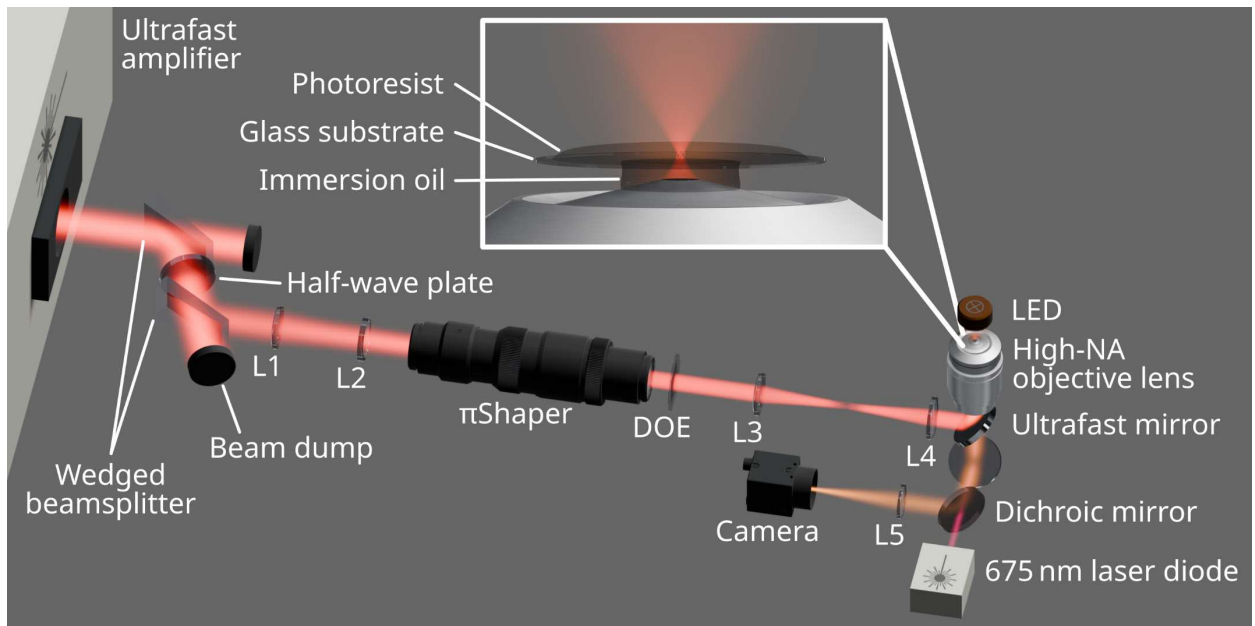
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788

789 **Extended Data Fig. 1: Figures of merit for different hyperparameter cases of the 100 μm**
 790 **trefoil knot.** Different marker styles show different polymerization thresholds I_{Thr}
 791 (normalized by $P_{\text{In}}/A_{\text{xs}}$), while the color scale shows the void penalization factors C_{Void} . Better
 792 structures are towards the lower right.

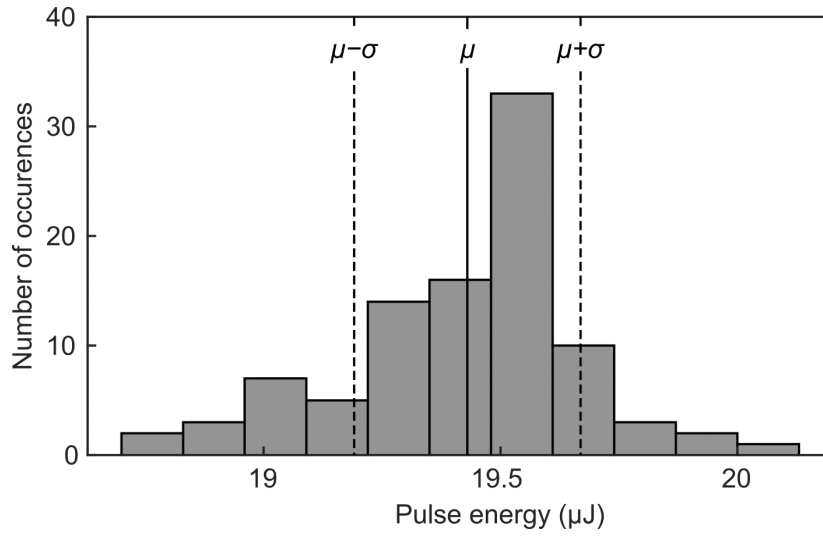


Extended Data Fig. 2: Simplified schematic of the optical setup for single-pulse holographic printing. The setup is described and the focal lengths f_1 - f_5 of lenses L1-L5 are given in the Methods.

Extended Data Table 1: Geometric properties and pulse energies for 3D printed objects.

Geometric properties corresponding to the optimization targets (shown in Extended Data Table 2) are given. Diffraction-limited voxel size is assumed as described in the introduction. Experimental pulse energy is measured during printing. Calculated pulse energy is obtained as described in the Methods.

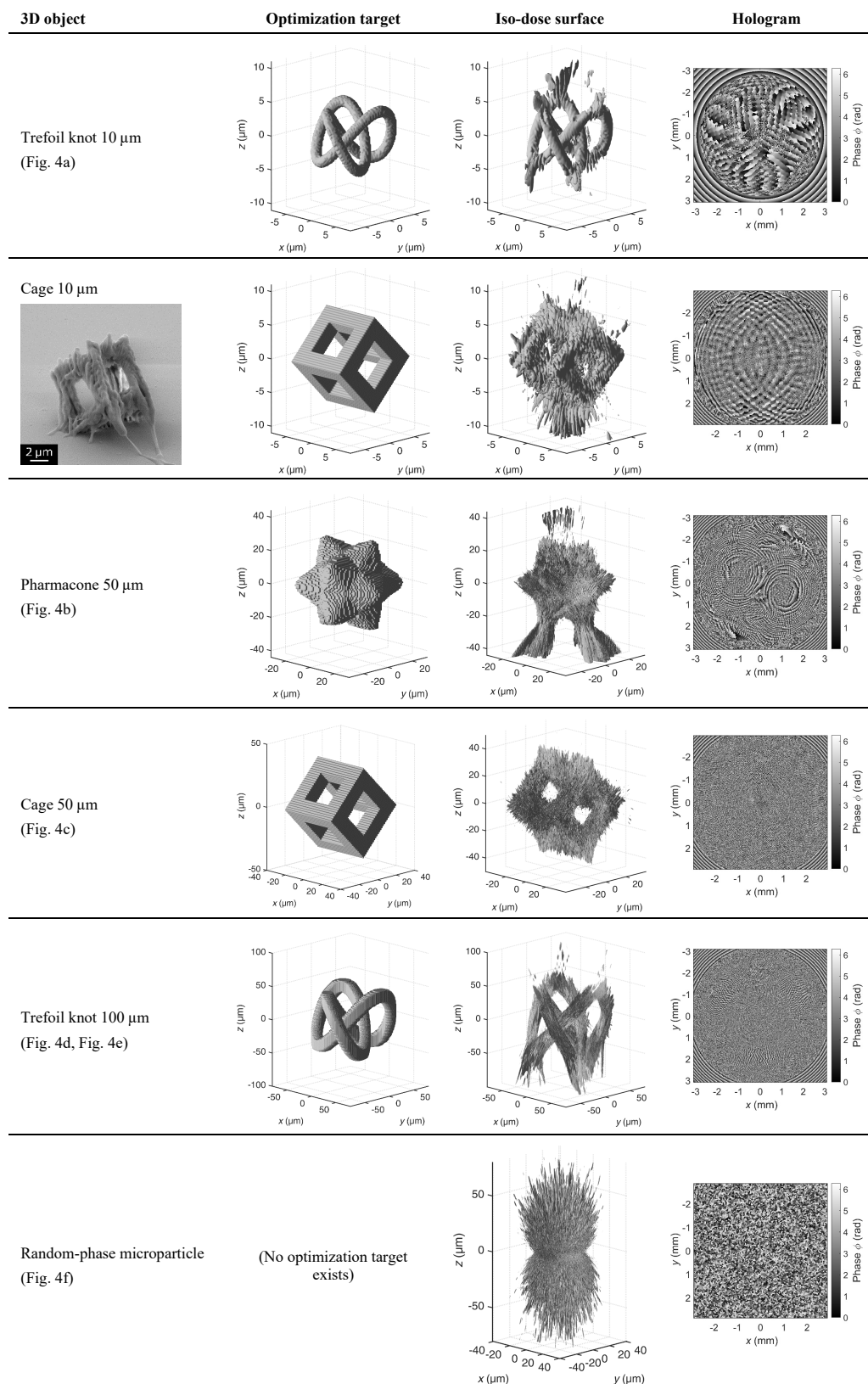
3D object	Axial length (μm)	Maximum cross-section (μm^2)	Volume (μm^3)	Number of voxels	Experimental pulse energy (μJ)	Calculated pulse energy (μJ)
Trefoil knot (Fig. 4A)	9.7	21	141	3,730	0.22	0.45
Cage (Extended Data Table 2)	14.3	70	491	12,933	0.41	0.8
Pharmacone (Fig. 4B)	52.3	1,960	60,250	1,588,618	2.5	5.5
Cage (Fig. 4C)	71.6	1,774	62,526	1,648,635	6.1	7.0
Trefoil knot (Fig. 4D)	97.3	2,948	213,392	5,626,542	11.2	11.0
Random-phase microparticle (Fig. 4F)	(No optimization target exists)	(No optimization target exists)	(No optimization target exists)	(No optimization target exists)	14.1	14.1

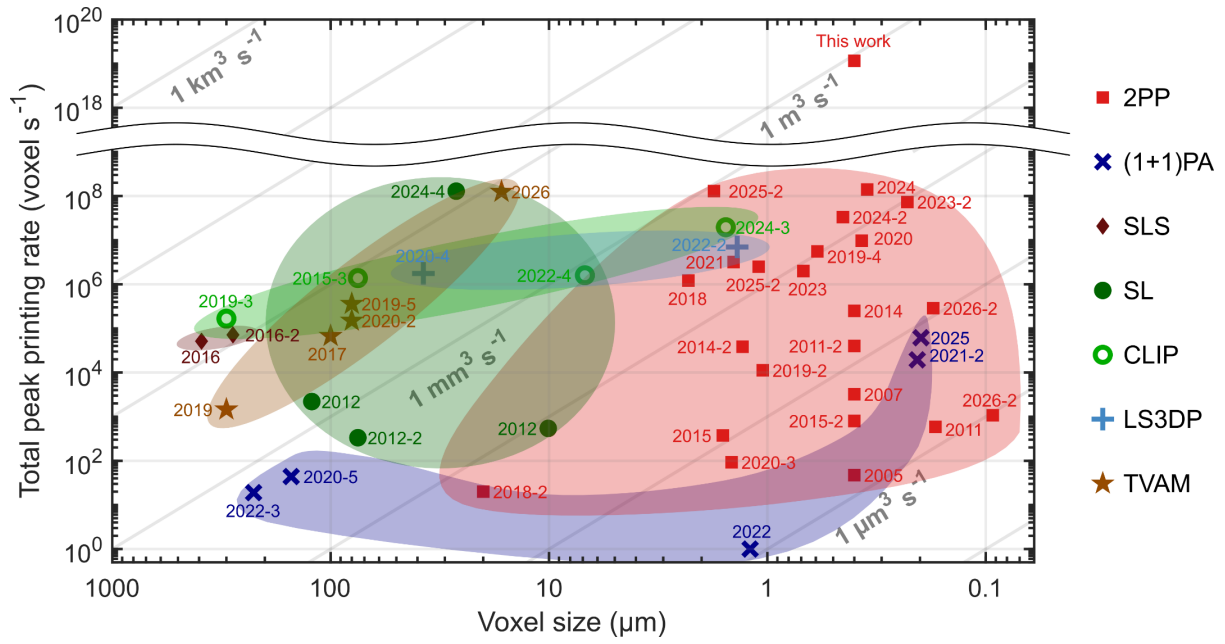


803

804 **Extended Data Fig. 3: Exposure-pulse energy distribution.** Histogram of pulse energies of
805 all 96 laser pulses (about 0.8 s apart) used to print the array of 100 μm trefoil knots shown in
806 Fig. 4e. Mean pulse energy $\mu=19.4$ μJ, standard deviation $\sigma=0.24$ μJ, relative standard
807 deviation $\sigma/\mu=1.2$ %. The given pulse energies correspond to the measurement position
808 before the π Shaper without correction for optical losses further in the beam path, see the
809 Methods.

810 **Extended Data Table 2: Optimized holograms and corresponding iso-dose surfaces.** For
811 each target structure, a hologram is calculated to yield an optimal iso-dose surface as
812 described in the Methods. Here, the shown iso-dose surfaces (pulse energies given in
813 Extended Data Table 1) include regions inside the glass substrate and regions unconnected
814 from the main 3D object. Optimization targets, iso-dose surfaces, and holograms are given
815 for all 3D objects shown in Fig. 4 and Fig. 5a. A SEM of a 10 μm cage, which is not included
816 in the gallery in Fig. 4, is provided.





Extended Data Fig. 4: Printing rate of various 3D printing technologies. Peak printing rates of light-based 3D printing technologies from the literature versus their average minimum voxel size. This figure shows the same data points as Fig. 5b. The legend entries refer to 2PP, Two-Photon Printing; (1+1)PA, Two-Step Absorption Printing; SLS, Selective Laser Sintering; SL, Stereolithography; CLIP, Continuous Liquid Interphase Printing; LS3DP, Lightsheet 3D Printing; TVAM, Tomographic Volumetric Additive Manufacturing. The labels refer to the references 2005⁵⁰, 2007⁵¹, 2011⁵², 2011-2⁵³, 2012⁵⁴⁻⁵⁷, 2012-2⁵⁸, 2014⁵⁹, 2014-2⁶⁰, 2015⁶¹, 2015-2⁶², 2015-3⁶³, 2016⁶⁴, 2016-2⁶⁵, 2017⁵⁴, 2018⁶⁶, 2018-2⁶⁷, 2019⁶⁸, 2019-2⁶⁹, 2019-3⁷⁰, 2019-4⁷¹, 2019-5⁷², 2020³⁵, 2020-2⁷³, 2020-3⁷⁴, 2020-4⁷⁵, 2020-5⁷⁶, 2021⁴, 2021-2⁷⁷, 2022⁷⁸, 2022-2⁷⁹, 2022-3⁸⁰, 2022-4⁸¹, 2023⁸², 2023-2⁴⁰, 2024², 2024-2³⁶, 2024-3⁸³, 2024-4⁵, 2025⁸⁴, 2025-2³, 2026⁶, 2026-2⁸⁵, and this work.

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