Supporting Information

Simultaneous Printing and Deformation of Microsystems via Two-Photon Lithography and Holographic Optical Tweezers

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Microfabrication system description

Our microfabrication system (Fig. 2) combines two-photon lithography (TPL) and holographic optical tweezers (HOT). The TPL, HOT, and imaging subsystems use a 100x oil-immersion microscope objective (MO, Olympus Plan Apo Lambda, NA=1.45) and a three-axis micro-positioning stage (Thorlabs MAX341 and BSC203). The imaging system consists of two cameras (Basler ace acA1300-75gm) at 40x and 100x magnification, doublet lenses (L), beamsplitters (BS1, 50:50 R:T; BS2, 90:10 R:T), tube lens (TL, Thorlabs ITL200), dichroic filters (DF, ND6.0 at 532nm and 690-1040nm), and two collimated 617 nm LED illumination sources in both reflection and transmission configurations.

The TPL system includes a femtosecond laser (fs laser, Spectra-Physics MaiTai eHP DS), acousto-optic modulator (AOM, IntraAction ATM-802DA2 and ME-820-6), two low-dispersion mirrors (M), beam block (BB), beam expander system (BE, f=50 and 200mm lenses), 2D scanning mirror galvanometer (galvo, Thorlabs GVS012), 4-F telescope relay (two f=60 mm lenses), power sensor (Thorlabs S142C and PM100USB), and longpass dichroic mirror (DM2, λ_c=650 nm). The AOM and two-axis scanning mirror galvanometer are driven by an analog output module (National Instruments NI-9263). In-plane scanning is performed by the two-axis scanning mirror galvanometer and the sample is translated layer-by-layer using the micropositioning stage.

The HOT system includes a 532 nm continuous wave (CW) laser (Laser Quantum Opus 3W), liquid crystal polarization rotator (LCPR, Meadowlark Optics LPR-100-0532), beam block (BB), polarizing beamsplitter (PBS), beam expander (BE1, f=-50 and 200 mm lenses), mirror (M), 1920-by-1152 pixel phase-only spatial light modulator (SLM, Meadowlark Optics P1920-0532), 4-F telescope relay (f=200 and 250 mm lenses), and shortpass dichroic mirror (DM1, λ_c=567 nm). The custom Fresnel beam block[1] at the focal plane of the 4-F telescope relay consists of a 200-μm-diameter gold film deposited on a glass coverslip.

To generate the scan path for the TPL laser's writing spot, a standard computer-aided design (CAD) file is sliced into 3-μm-thick layers and a G-code scan path is generated for each layer using open-source software[2]. The G-code commands are then transformed into uniformly-spaced points using a MATLAB script and converted to voltage values for the analog output module that drives the scanning galvanometers.

Material characterization

Absorbance spectrum

The photopolymer used for the TPL/HOT experiments consists of 1.1% w/w TPO-Li (Colorado Photopolymer Solutions), 60.5% w/w deionized (DI) water, 38.4% w/w SR9035 (Sartomer).

In order to enable simultaneous TPL and HOT operation, our resin had to be polymerizable by the 760 nm scanning pulsed laser while remaining inert to the 532 nm optical trapping laser. To verify that our resin met these demands, we characterized its absorbance spectrum with Agilent/HP 8453 UV-visible spectrophotometer (Fig. S1). The spectrum indicates a near-zero absorbance at 532 nm. However, some degree of polymerization is observed when traps with high power levels (e.g., >100mW) are used. This is mainly a result of thermal polymerization–not photopolymerization.
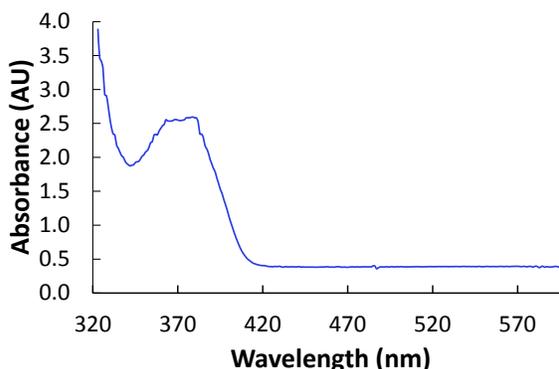
Figure S1. Absorption spectrum of our photopolymer resin. The resin is absorptive at the one-photon wavelength of 380 nm (resulting in two-photon absorption at 760 nm). The resin also shows negligible absorption at 532 nm, the wavelength of the HOT handling laser.

Refractive index measurements

The refractive index of the resin was measured using an Atago USA 1212-NAR-1T solid Abbe refractometer. The refractive index of the liquid prepolymer resin is 1.3918 and the solid polymerized resin is 1.4912.

Print resolution measurements

To characterize our system's printing resolution, pulsed laser power was measured directly before the microscope objective using a Thorlabs S470C thermal power sensor. Multiple test structures (Fig. S2a) were printed with 70.1 mW at different scanning speeds and the resulting thickness of the printed lines were measured using scanning electron microscopy (SEM, JEOL

7500F). The relationship between the printed line width and the laser beam scanning speed is provided in Fig. S2b.
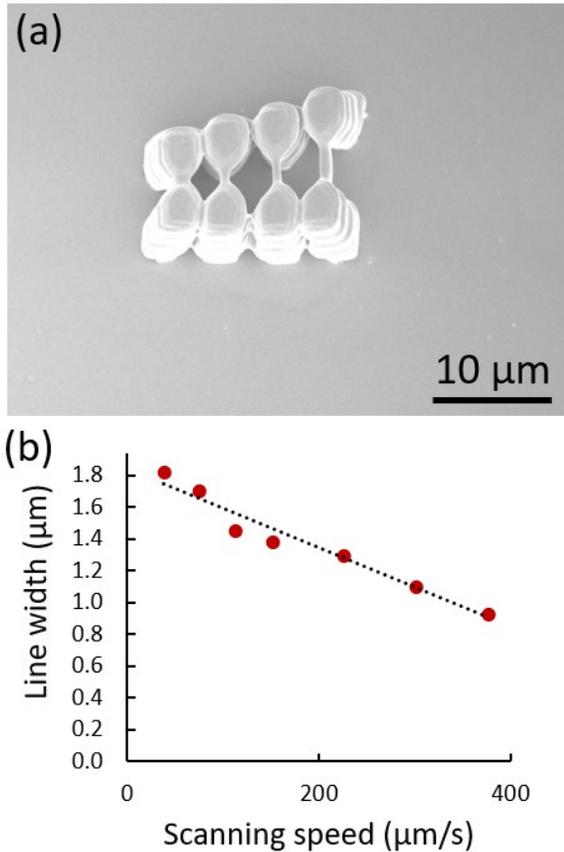
Figure S2. (a) SEM characterization of TPL-printed structures; (b) relationship between line width and laser scanning speed.

Simulation tool

In this section we describe the ray-optics-based simulation tool for calculating optical forces and moments on micro-bodies of any arbitrary shape. The MATLAB simulation tool is called the *STL Compatibility Add-on* and it is designed to work with version 1.0.1 of *OTS – the Optical Tweezers Software*[3,4].

The STL Compatibility Add-on is designed to work with binary-formatted *.stl* files (not ASCII-formatted *.stl* files).

Installation

The STL Compatibility Add-on can be installed via the following steps, which are also detailed in the included *readme.txt*. First, download[3] and unzip the OTS 1.0.1 software. Next, place all MATLAB files (i.e., those with file extension *.m*) from the STL Compatibility Add-on into the "go" folder in the main "ots1.0.1" directory. Five MATLAB files will be new (*STLShape.m*, *ParticleSTLShape.m*, *stlread.m*, *polyhedronCentroid.m*, and *example_particleSTLshape.m*) and one will be a replacement of an existing file (*Ray.m*). Finally, run *OTS.m* in the main "ots1.0.1" director to load all files onto MATLAB's working path and use *example_particleSTLshape.m*

and *StrainEnergyLattice.STL* to visualize forces on the embedded-strain-energy lattice presented in the main manuscript (Figs. 1 and 4).

Description of included files

- *STLShape.m* is a class designed to handle raw STL face and vertex data. It includes methods for scaling, translating, rotating, and calculating statistics on particle-ray intersections.
- *ParticleSTLShape.m* is a class designed to handle STL shape data, as contained in the *STLShape* subclass, as an optically-trappable particle that can be simulated. This class includes methods for calculating scattering events, forces, and moments.
- *Ray.m* is an updated version of the *Ray.m* file included in the standard OTS 1.0.1 software. It includes additional optimization for calculating particle-ray intersections on arbitrarily shaped particles. The code for calculate particle-ray intersections on standard cylindrical and spherical particle types is unmodified.
- *polyhedronCentroid.m* is a function used to locate the centroid of arbitrarily shaped particles for the purpose of calculating moments. It was written by D. Legland and distributed as a part of the *geom3d* MATLAB toolbox[5].
- *stlread.m* is a function used to parse standard *.stl* files into face and vertex information. It was written by E. Johnson[6].
- *example_particleSTLshape.m* is a demonstration script used to illustrate how to set up an optical force simulation with the STL Compatibility Add-on. The code is commented to describe individual simulation parameters.
- *StrainEnergyLattice.STL* is an example STL file used in *example_particleSTLshape.m*. It represents the embedded-strain-energy lattice described in the main manuscript (Figs. 1 and 4).
- *readme.txt* describes the STL Compatibility Add-on installation steps listed in the previous section.

References

1   L. A. Shaw, S. Chizari and J. B. Hopkins, *Appl. Opt.*, 2018, **57**, 6396.

2   Slic3r: G-code generator for 3D printers, http://slic3r.org/.

3   G. Volpe, OTS — the Optical Tweezers Software, http://opticaltweezers.org/software/ots-the-optical-tweezers-software/.

4   A. Callegari, M. Mijalkov, A. B. Gököz and G. Volpe, *J. Opt. Soc. Am. B*, 2015, **32**, B11.

5   D. Legland, MATLAB Central - geom3d, https://www.mathworks.com/matlabcentral/fileexchange/24484-geom3d.

6   E. Johnson, MATLAB Central - STL File Reader, https://www.mathworks.com/matlabcentral/fileexchange/22409-stl-file-reader.