Week 08: Light-Matter Interactions

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Lecture Overview

- Momentum of light and optical tweezers
- Plasmon resonance and stimuli responsive gels

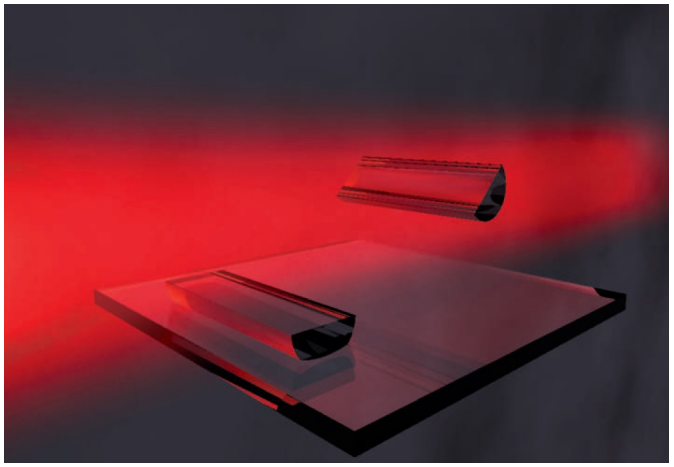
Beam-powered propulsion or Light craft (video)

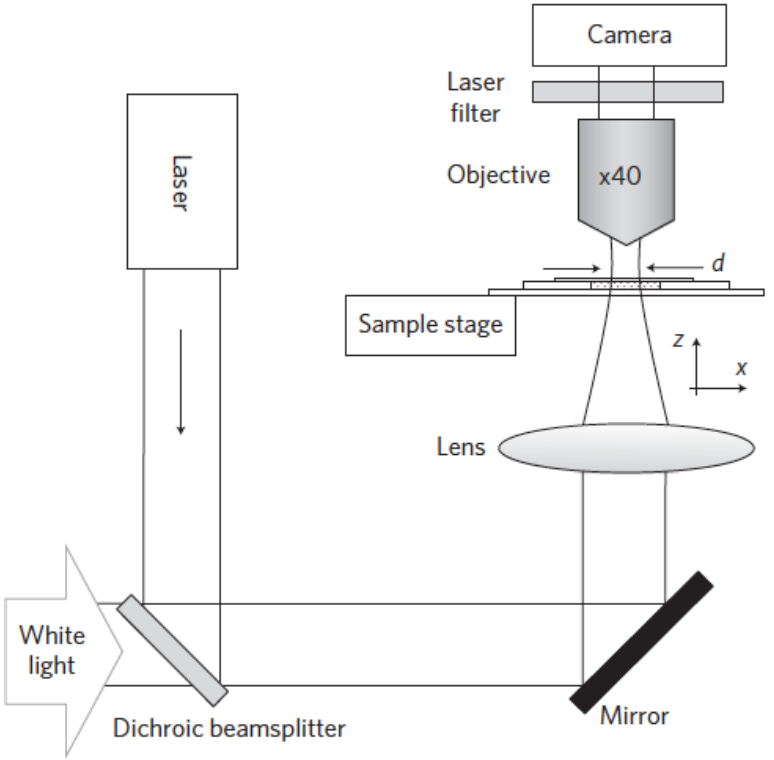
- Solar (light) Sails
  - Radiation pressure exerted by the light source
  - Einstein's relation: $p = E/c$ (E: energy of the photon or flux, c: speed of light)
  - Thin reflective mirror
  - Analogous to sailing boat; light-mirror vs wind-sail

- Laser-energized Rocket
  - **Thermal rockets**: Laser beam heats the liquid propellant and converts it to gas. Exhaust.
  - **Ablative propulsion**: External pulsed-laser burn off a plasma plume from a solid metal propellant or evaporate/sublimate material. Ablated material applies a pulse of high pressure to the surface underneath as it expands (hammer).

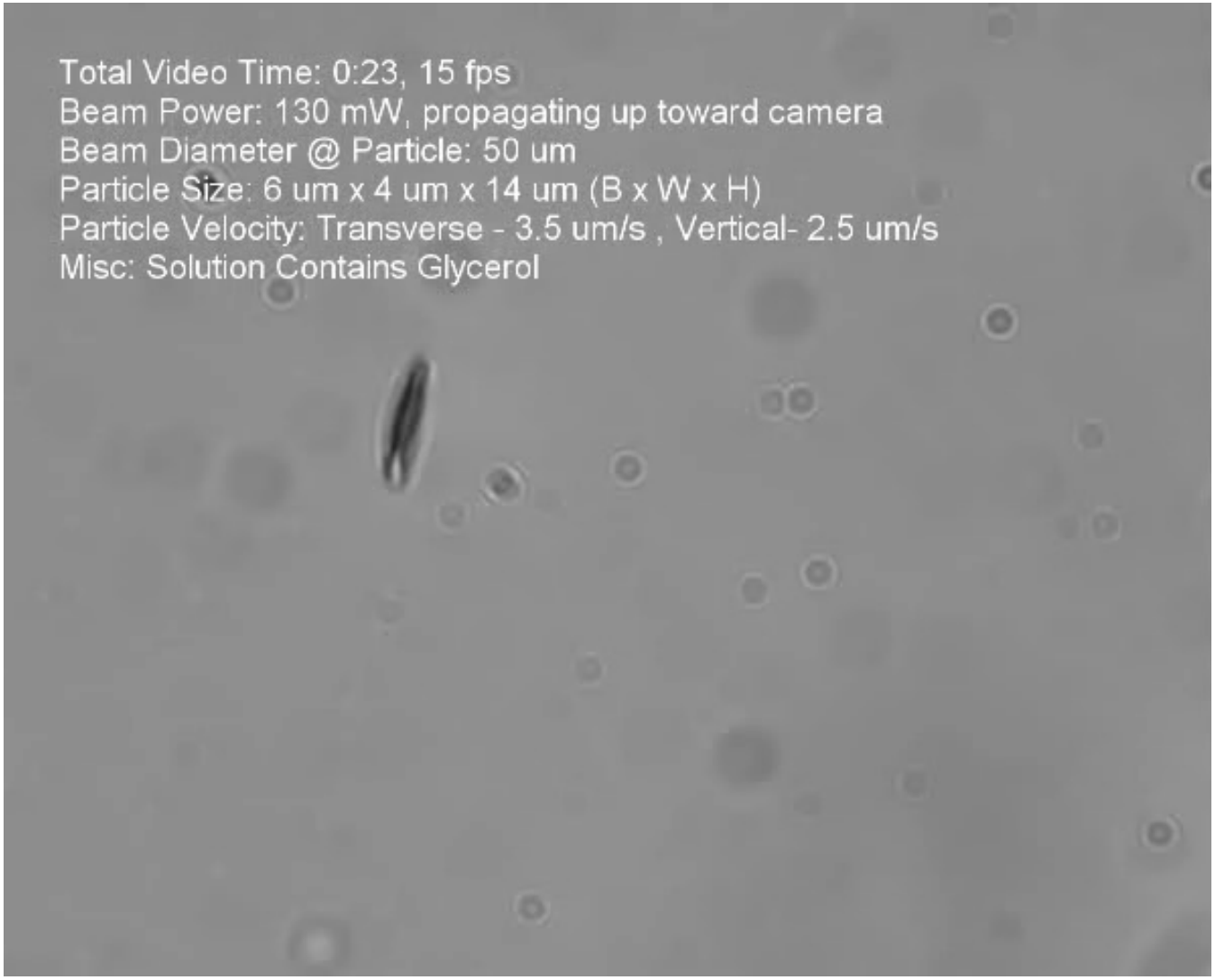
Optical Lift

- Analogous to aerodynamic lift
- Cambered refractive object with differently shaped top and bottom surfaces: experience transverse lift under uniform stream of light
- A few milliWatts of focused laser generate force in picoNewton range
- Gradient force is negligible,
- Light scattering generates the lift
- Hemicylinders
- Stable attack angle: 55





Optical Lift



Light-matter interactions

- Thermal forces (radiometric forces)
  - Temperature gradients in the medium surrounding the object
  - Thermal expansion of solids
  - Thermophoresis of microparticles
  - Phase transitions (liquid-gas-plasma)
  - Thermocapillary convective flows

- Radiation pressure
  - Transparency
  - Refractive index

Optical tweezers

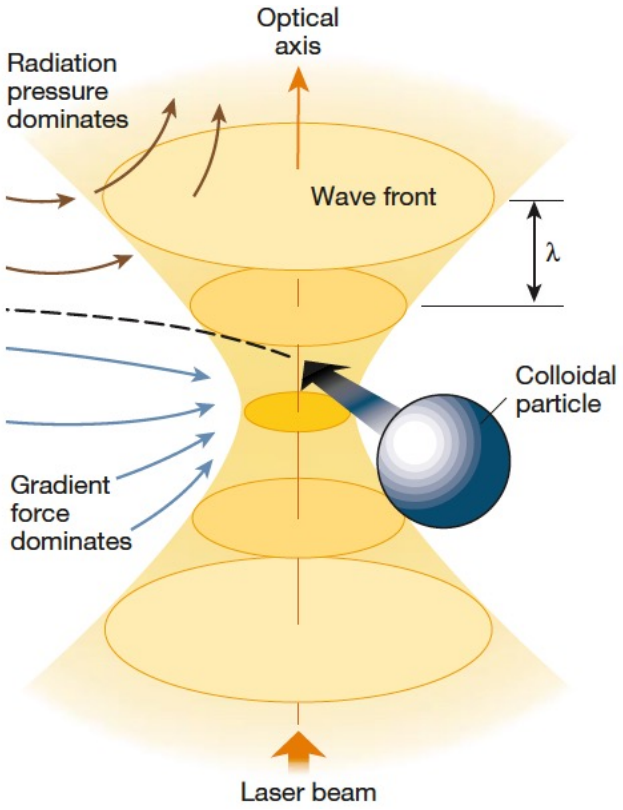
- **Maxwell**: Momentum transfer from the electromagnetic field to an object, due to absorption or reflection, should result in a radiation pressure in the propagation direction of the wave.

- Optical potential well or optical bottle
  - Tailor the properties of electromagnetic field to generate a pattern of intensity gradients that can act as a 3D trap
  - Adjusting the location of the trap allows the particle to be moved
  - Optical forces act in a highly localized space
  - Particle size and refractive index difference matter

- Spatial light modulators (liquid crystal displays) create holographic optical patterns and multiple optical traps

Optical tweezers (video)

- Non-uniform spatial distribution of light in the vicinity of the beam focus: a gradient force
- A scattering levitation force along the beam axis: harmonic oscillator



Optical force at a single point on the surface

$$\langle \mathbf{f} \rangle = \frac{1}{4} |E|^2 \Delta \epsilon \delta(\mathbf{n}) \hat{\mathbf{n}}$$

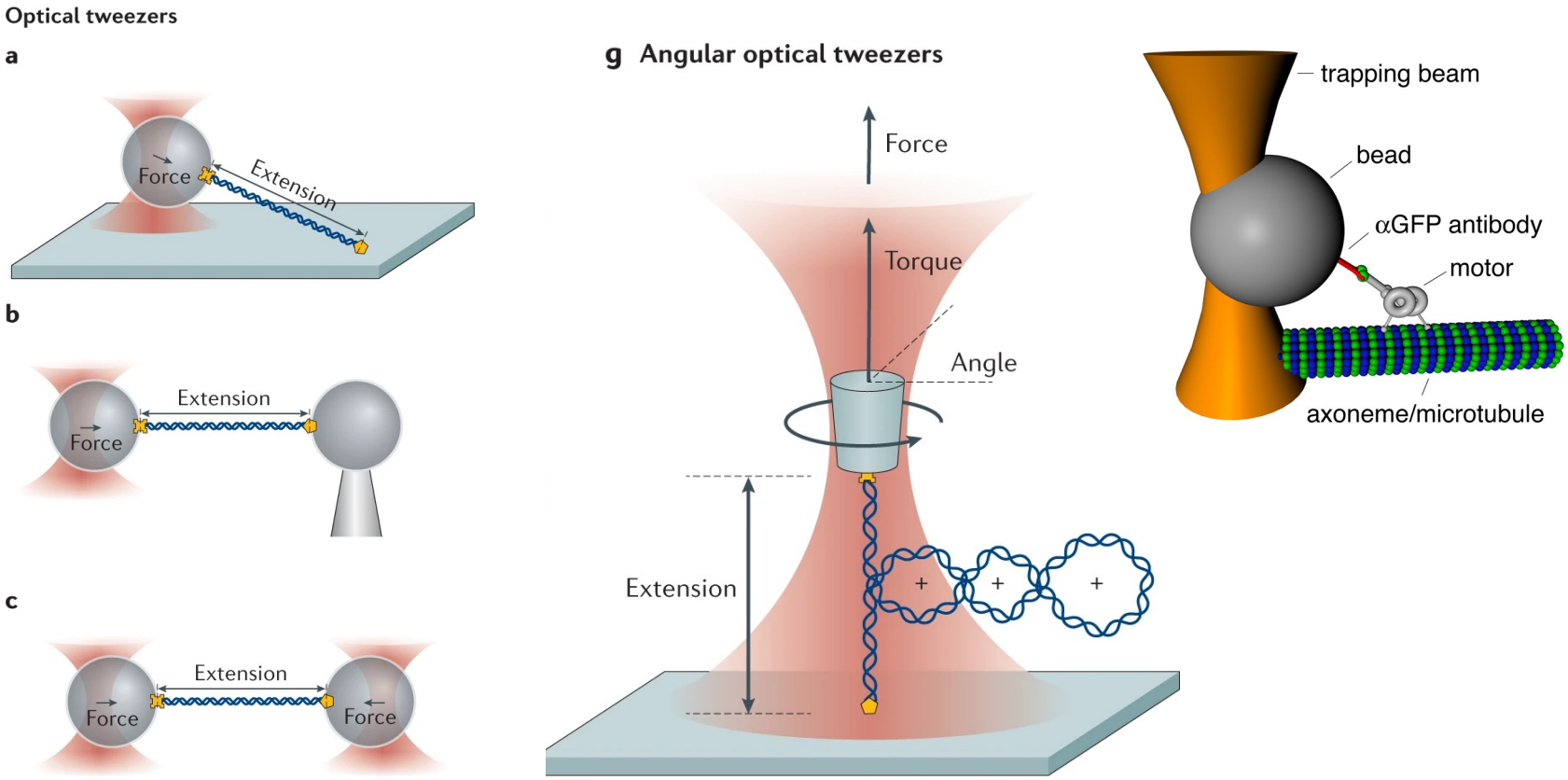
E: total electric field acting on the surface element

ϵ : Dielectric constant

n: Unit surface normal

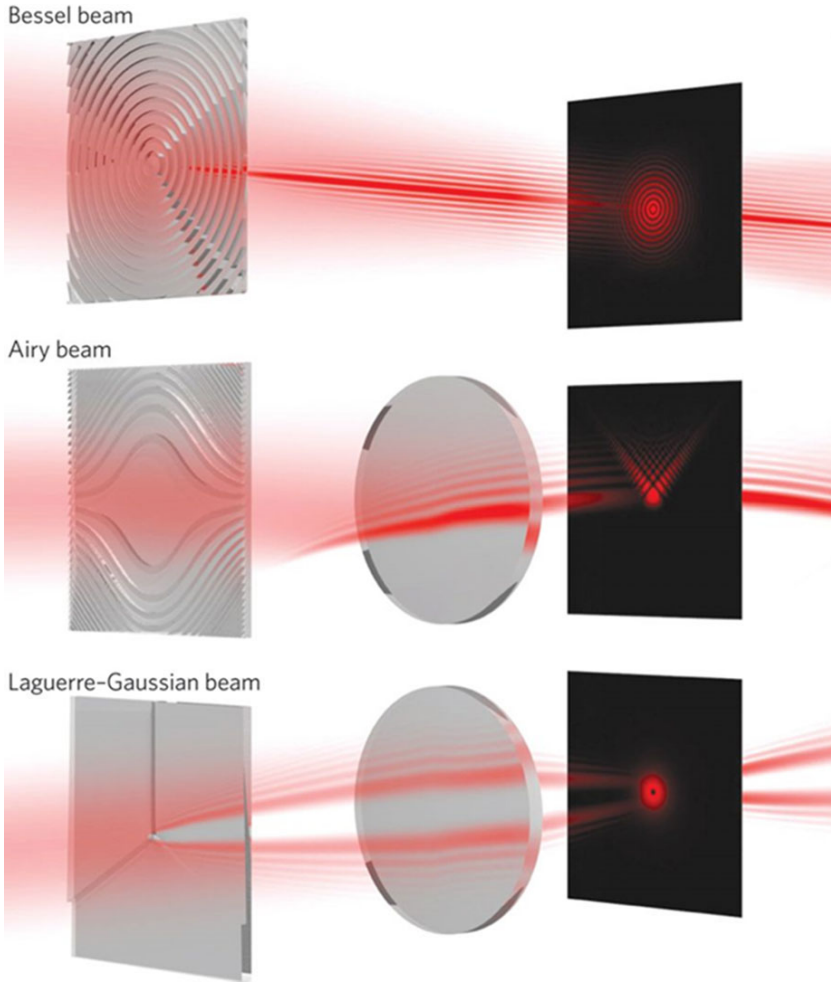
δ : Dirac delta function centered at the material surface

Optical tweezers and biophysics

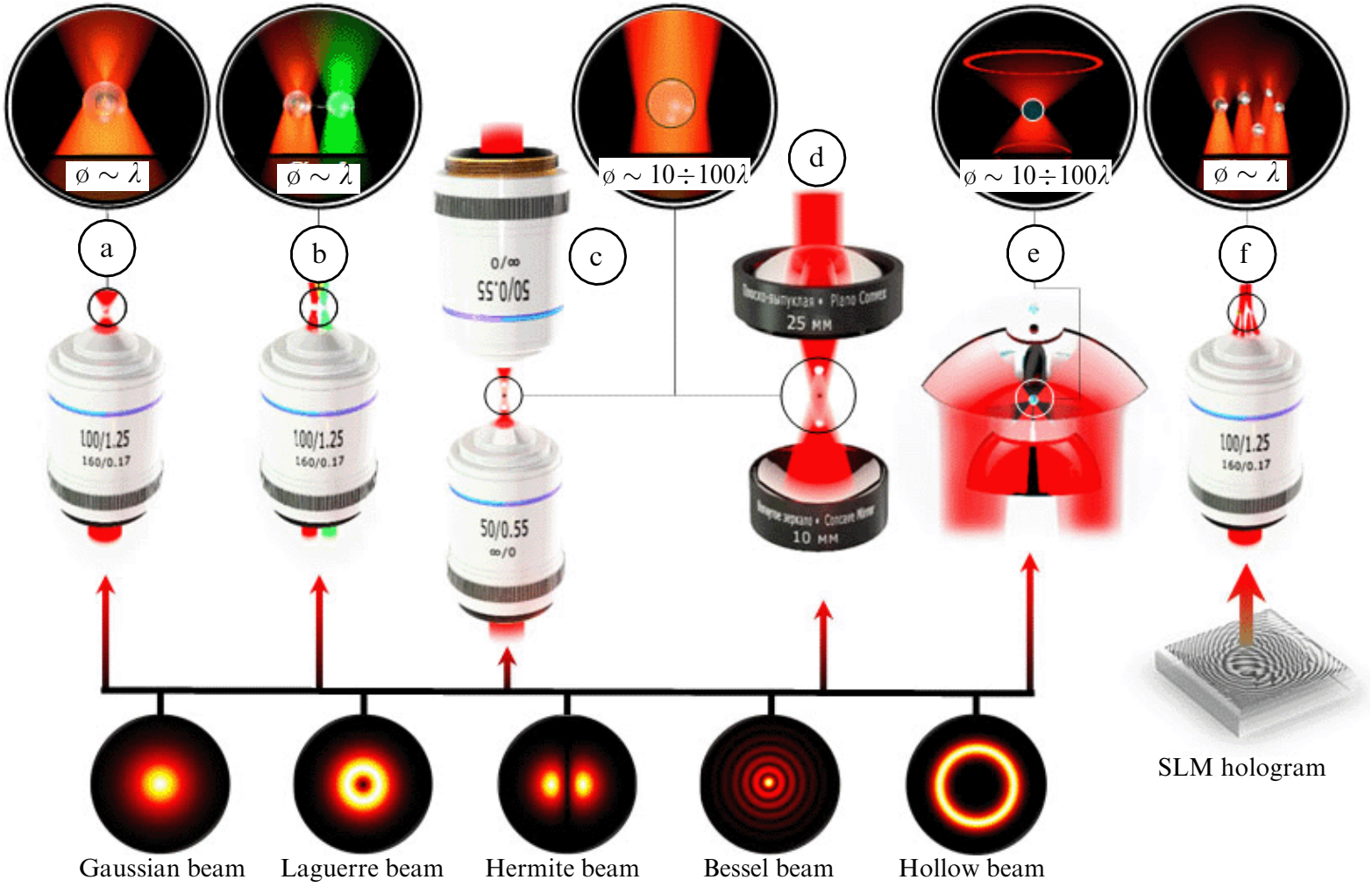


Beam shaping with diffractive elements

- Microfabricated diffractive optical elements

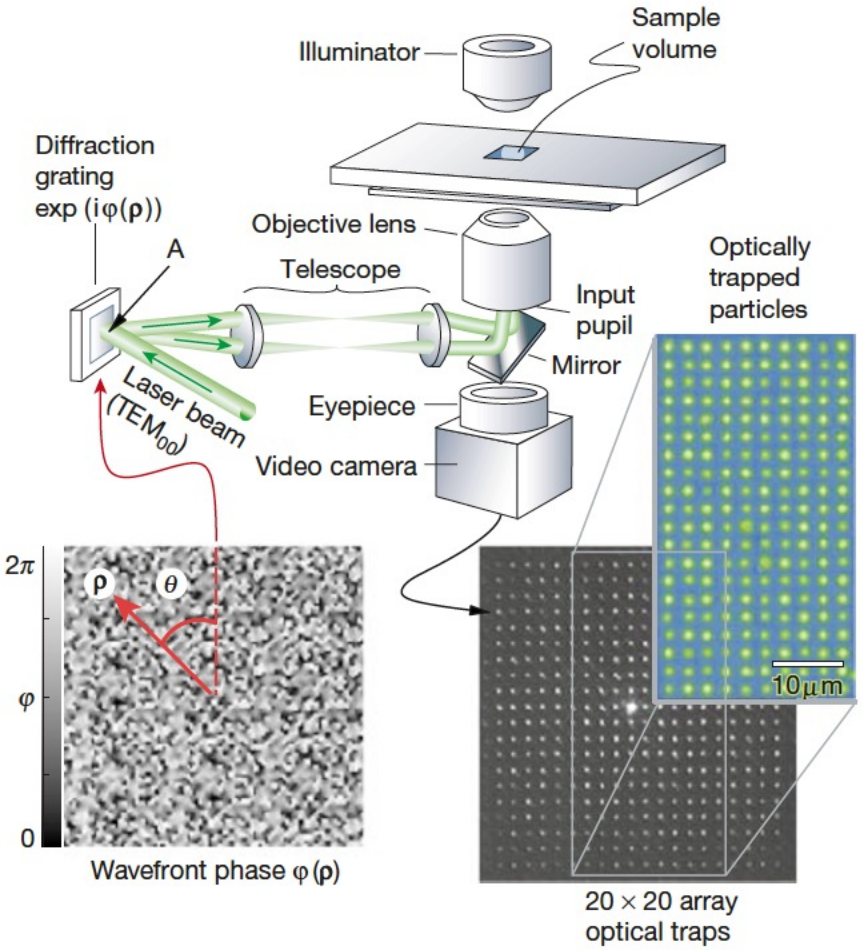


Optical trapping systems



Digital holograms

- A large number of optical tweezers



Holographic optical tweezers

- A dielectric particle approaching a focused beam of light is polarized by the light's electric field and then drawn up intensity gradients toward the focal point. Radiation pressure competes with this optical gradient force and tends to displace the trapped particle along the beam's axis.

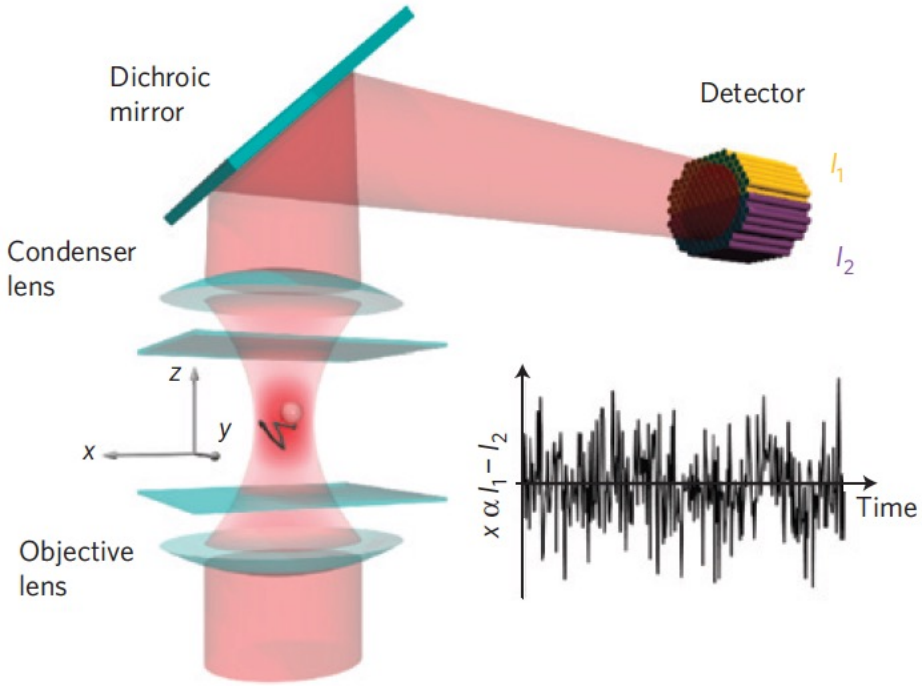
- An optical trap can be placed anywhere within the objective lens' focal volume by appropriately selecting the input beam's propagation direction and degree of collimation

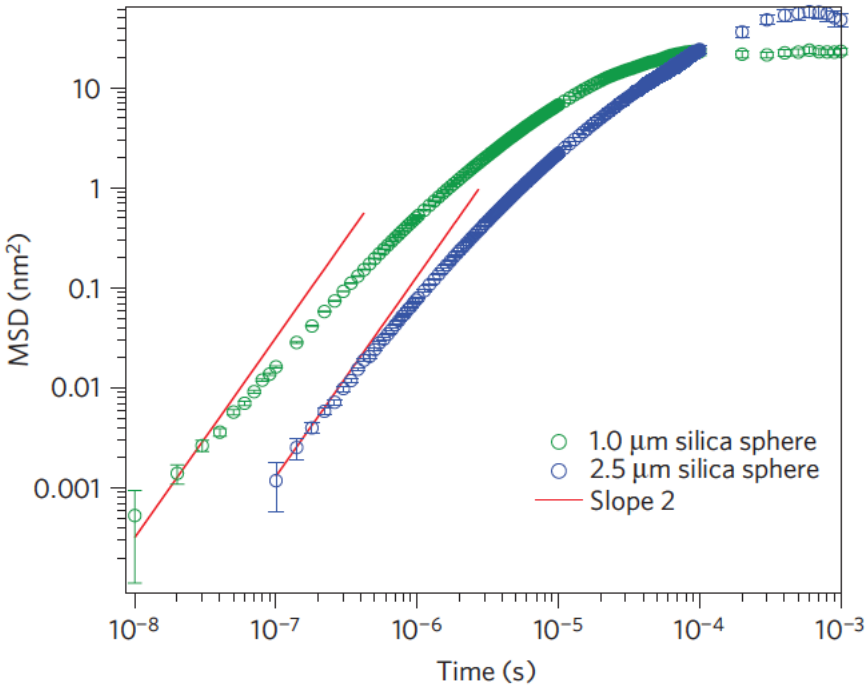
- Multiple beams entering the lens' input pupil simultaneously each form optical traps in the focal volume, each at a location determined by its degree of collimation angle of incidence

- Link: https://physics.nyu.edu/grierlab/dynamic4c/

On Brownian Motion

- An optical trap with 75 MHz bandwidth and sub-angstrom precision





On Brownian Motion

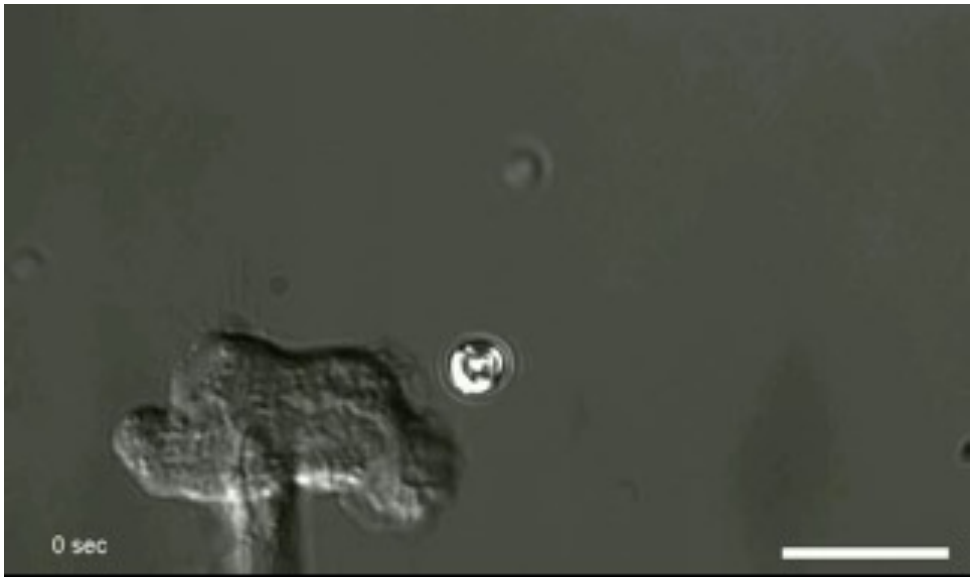
- Multiple regimes
- Random movement of Brownian particles in a liquid at large timescales
- Einstein and Robert Brown $\mathrm{MSD}(t) = 2Dt$ $\tau_p = m/\gamma$ Stokes drag coefficient
- Ballistic motion at small scales: After receiving an impulse from the surrounding fluid molecules, the particle flies in a straight line with constant velocity before collisions with fluid molecules slow it down
- Langevin $\mathrm{MSD}(t) = (k_B T/m)t^2$
- Hydrodynamic memory effect: Inertia of the fluid leads to long-lived vortices caused by and in turn affecting the particle's motion
- Vladimirsky and Hinch (added mass)

$$\mathrm{MSD}(t) = (k_B T/m^*)t^2 \qquad \tau_f = r^2 \rho_f/\eta$$

$$m^* = m_p + m_a \qquad m_a = \tfrac{2}{3}\pi r^3 \rho_f$$

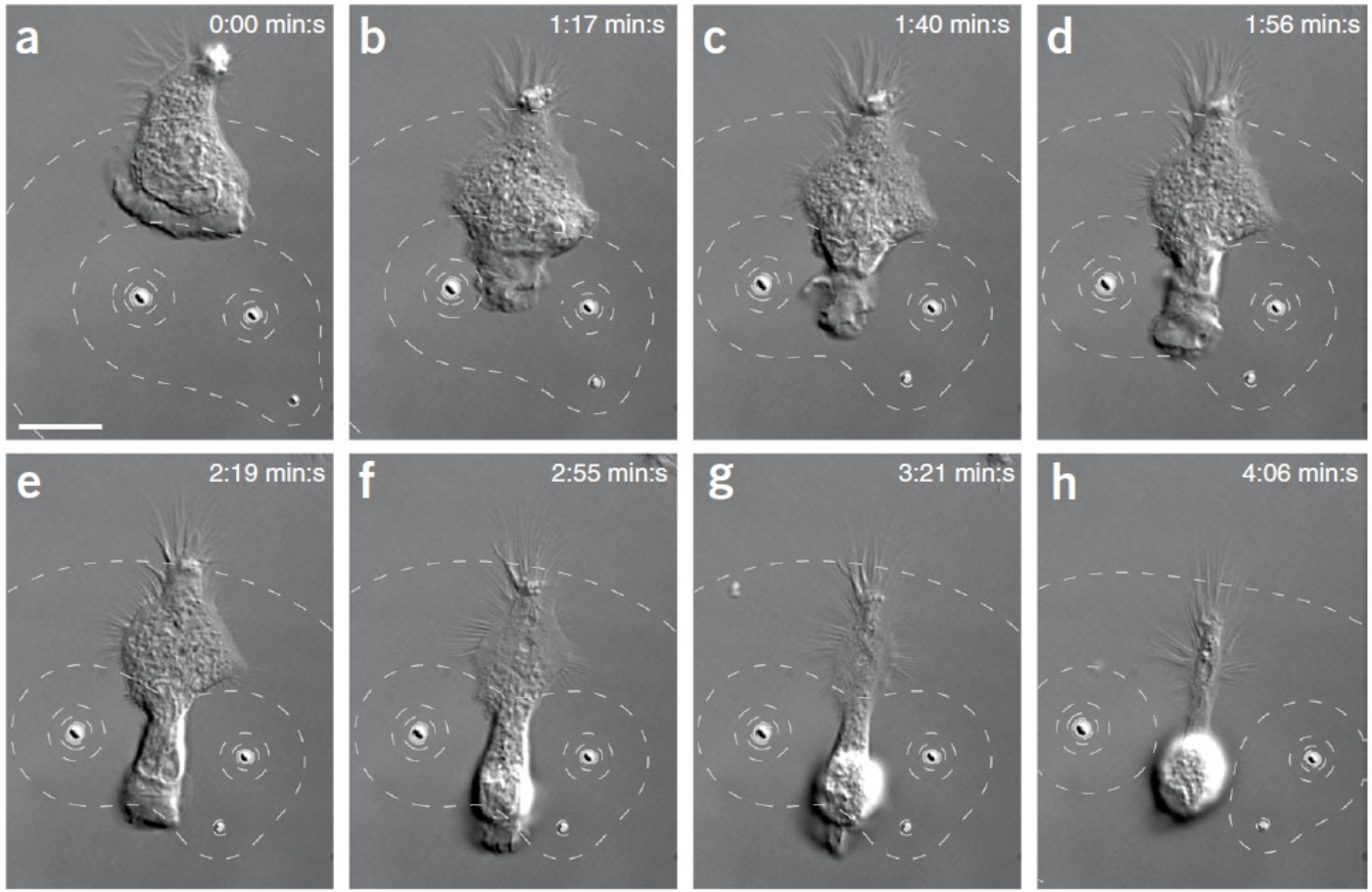
Optically actuated microtools

- Cell stimulation with optically manipulated drug-loaded polymer particles (2 um)

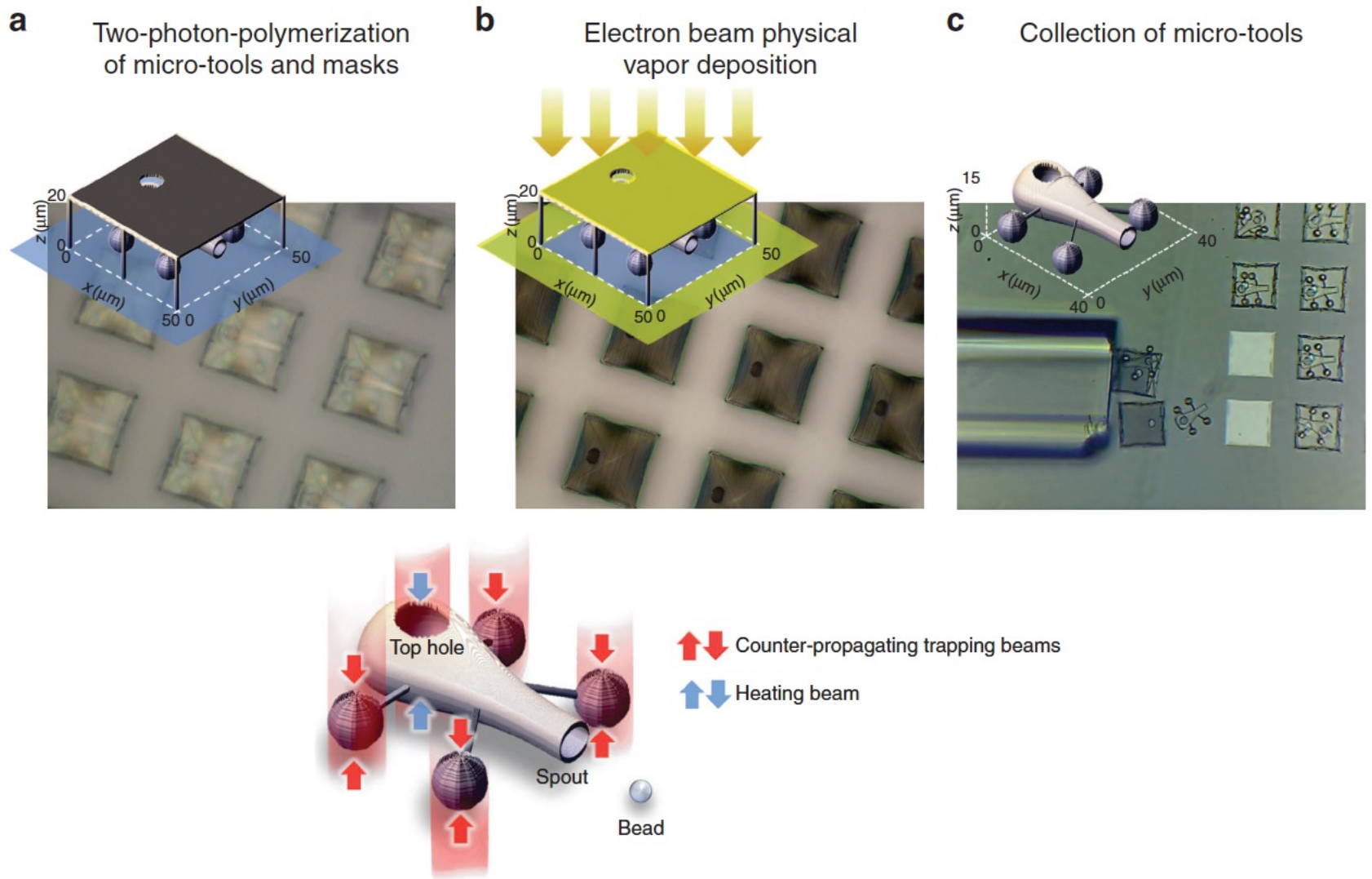


Optically actuated microtools

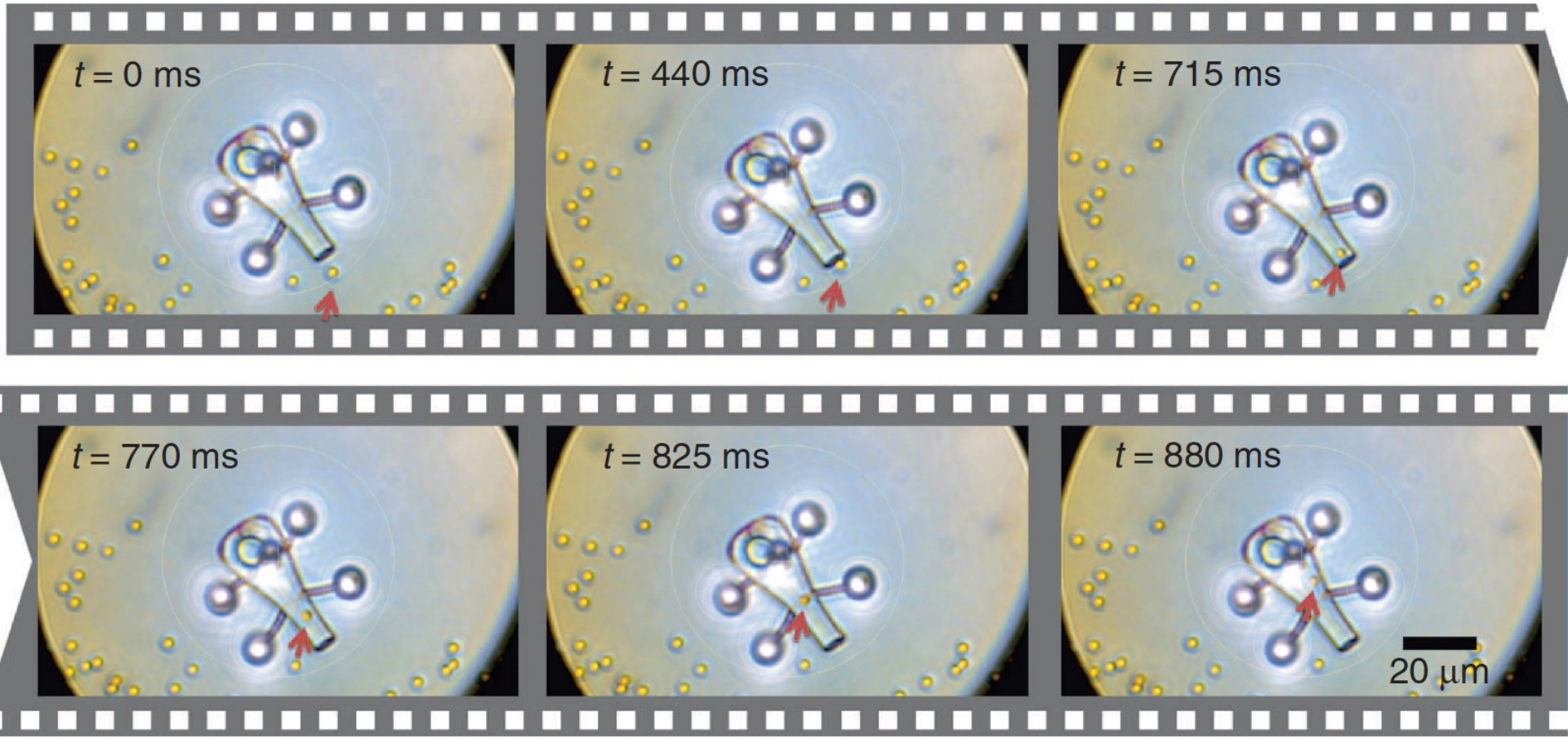
- Multiple source of Cytochalasin D (actin depolymerization)



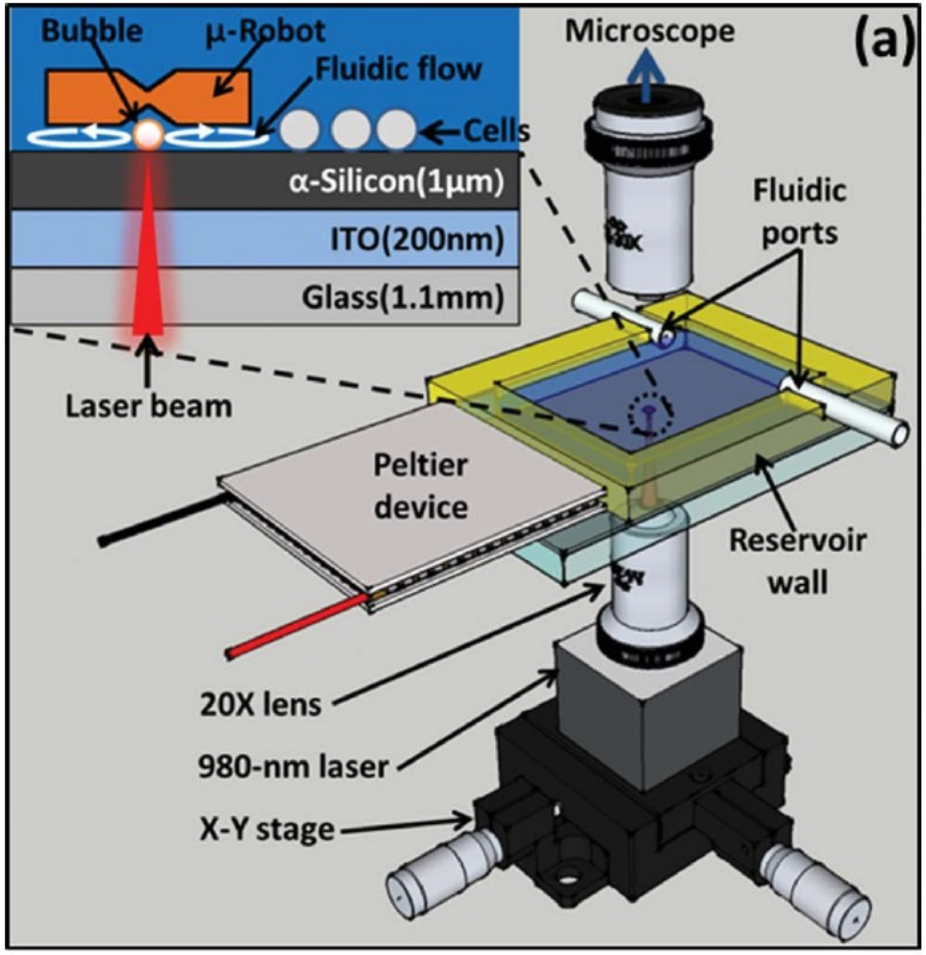
Optically actuated microtools

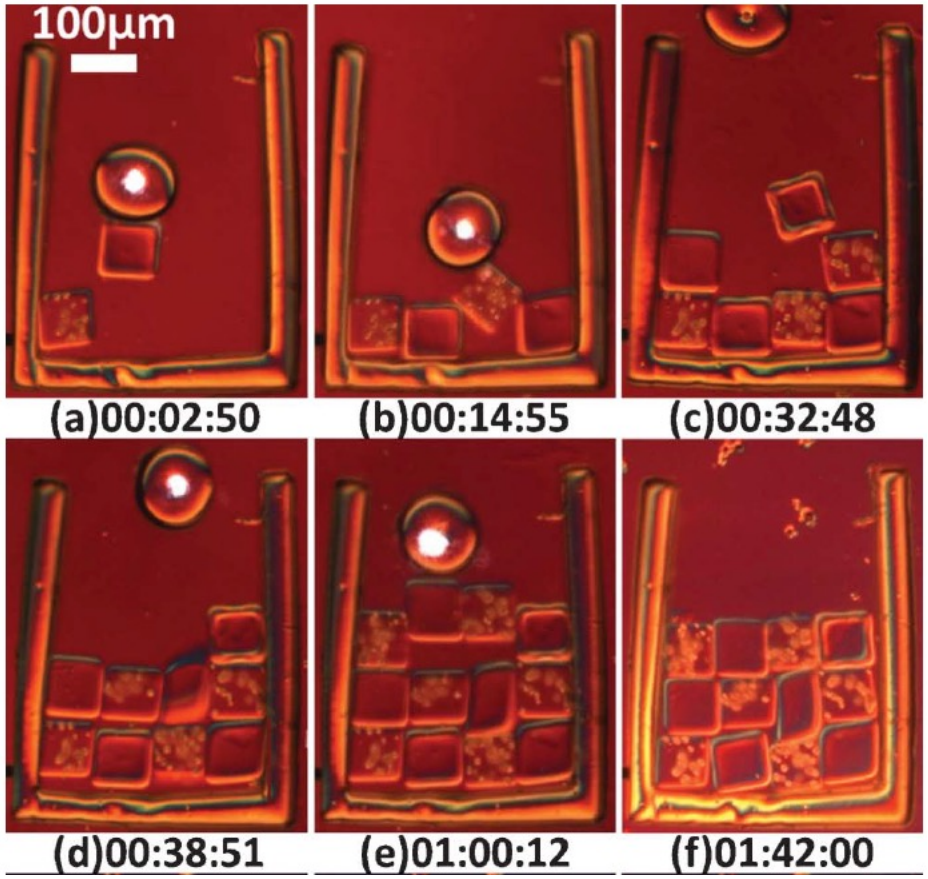


Optically actuated microtools



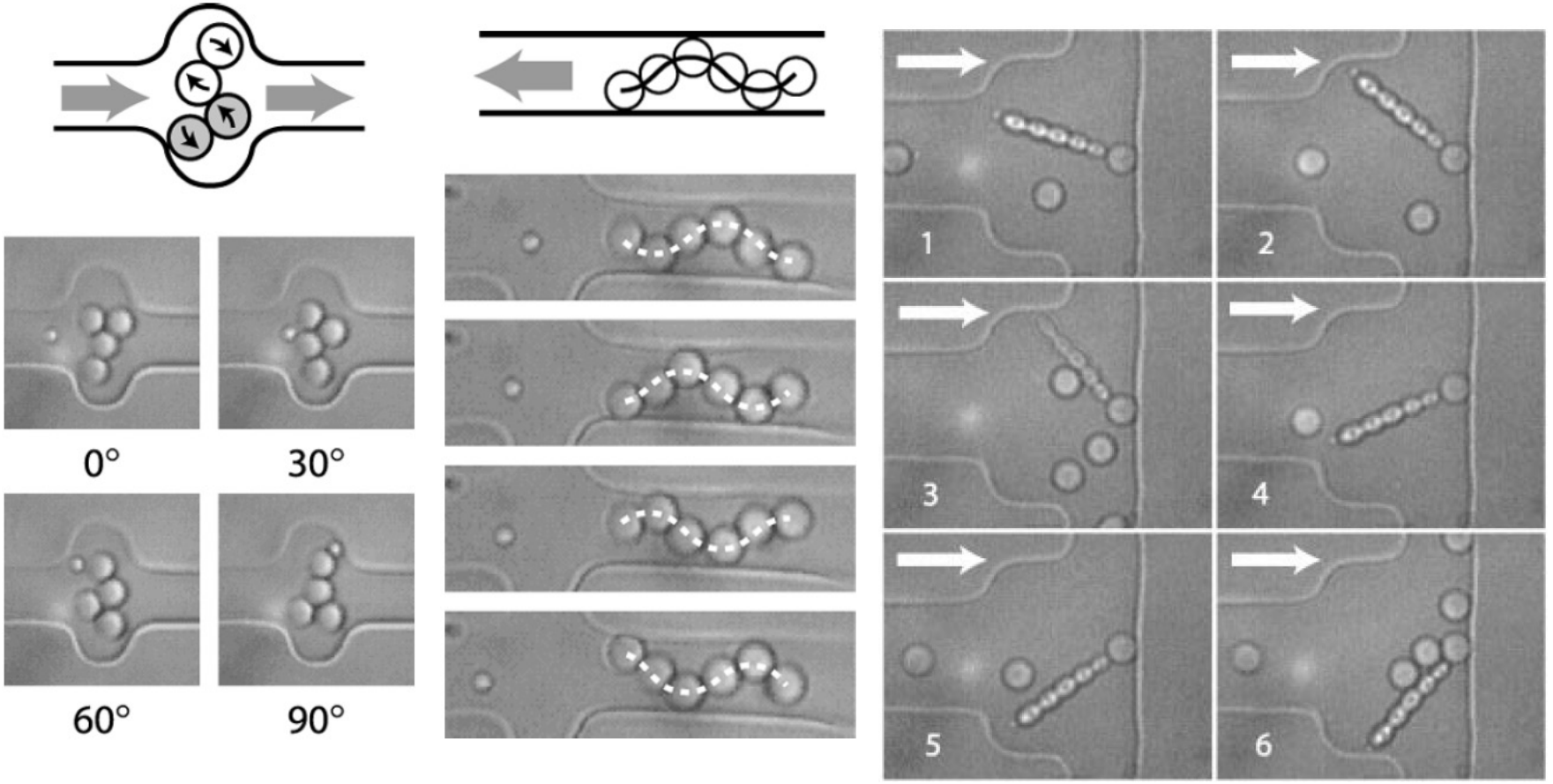
Optically actuated microtools



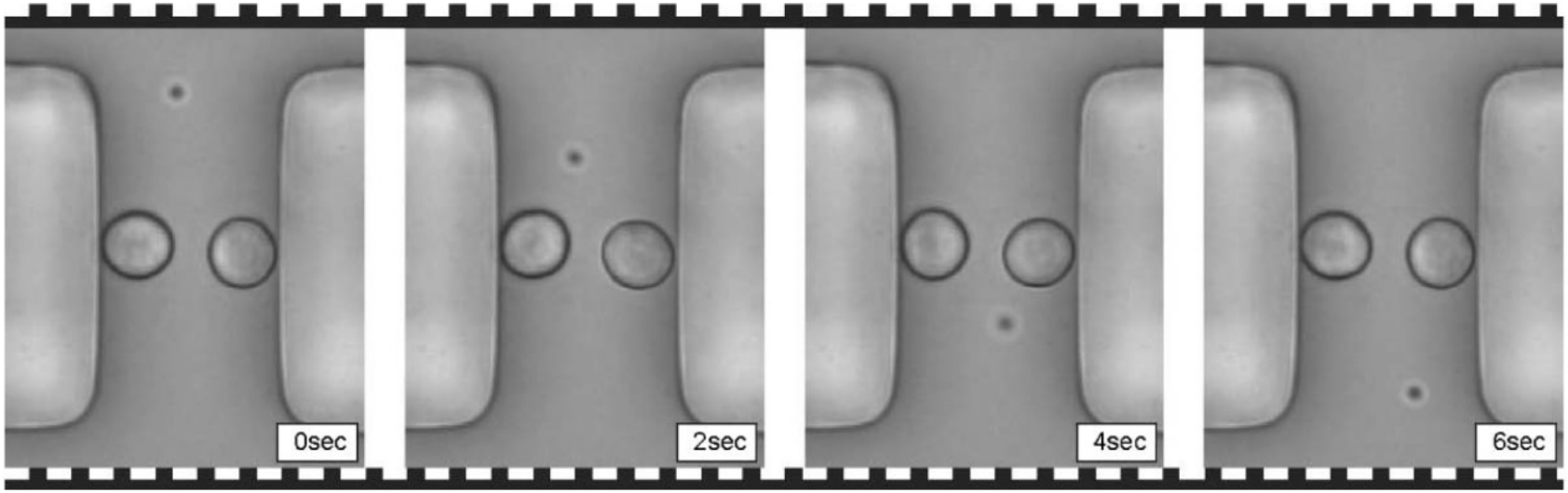


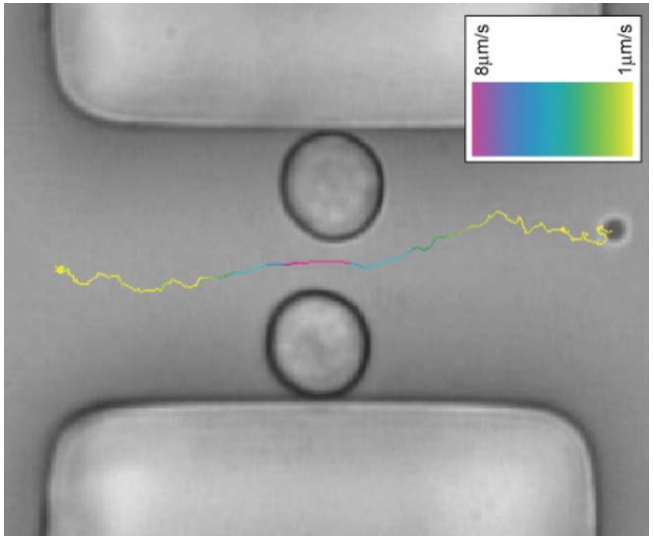
Optically driven valves and pumps

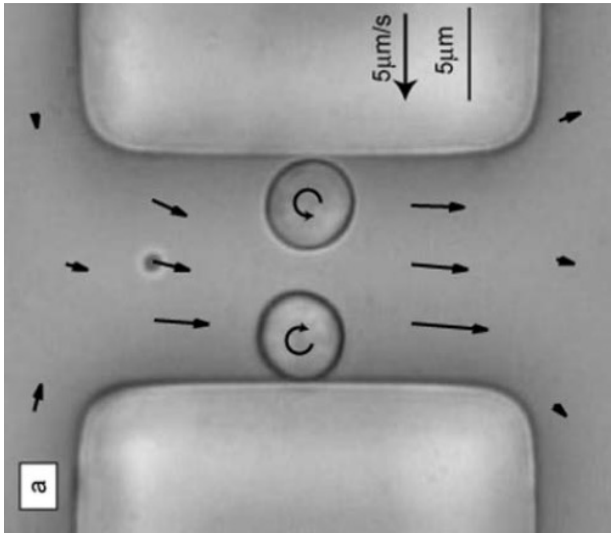
- Structures assembled from colloidal particles



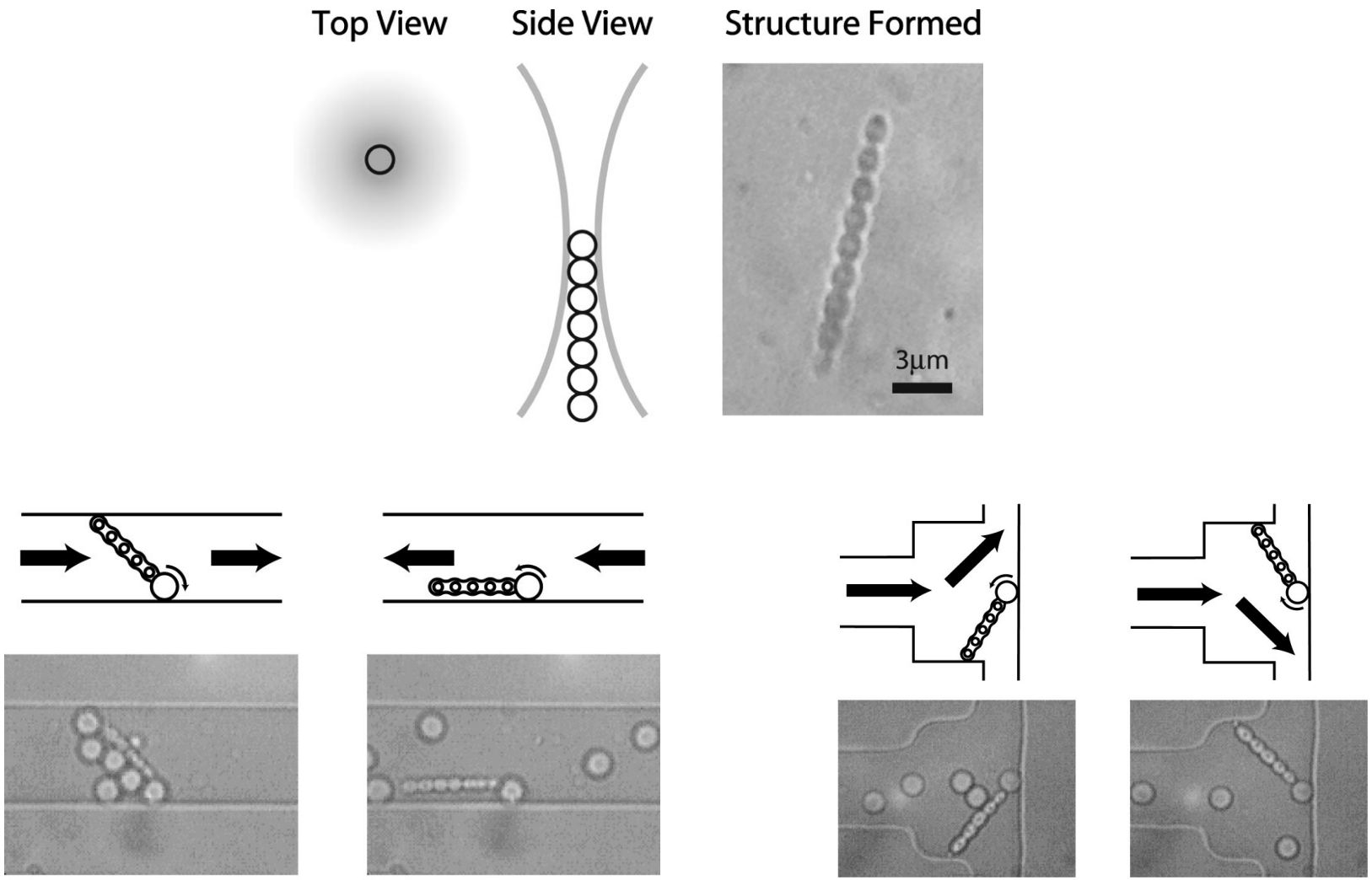
Optically driven valves and pumps





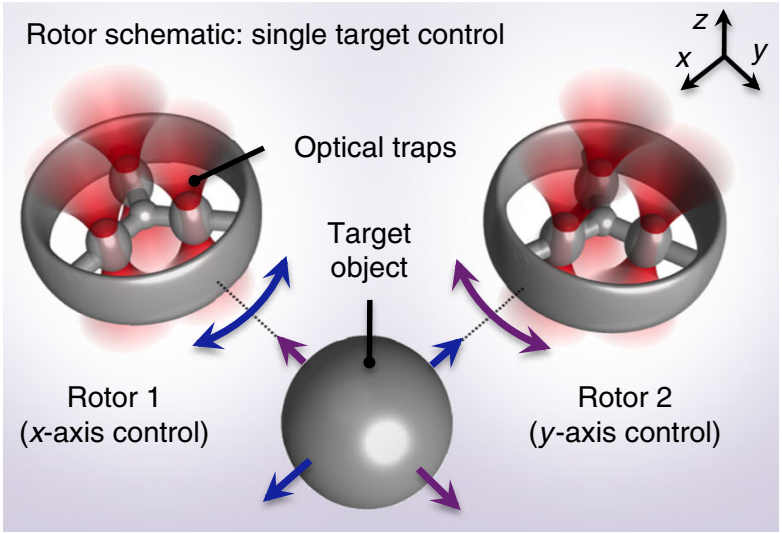


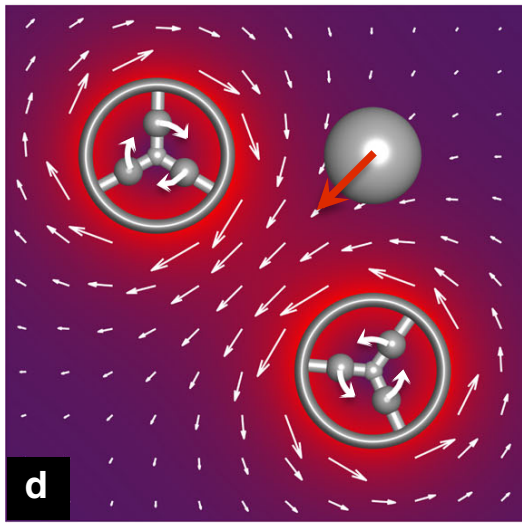
Optically driven valves and pumps

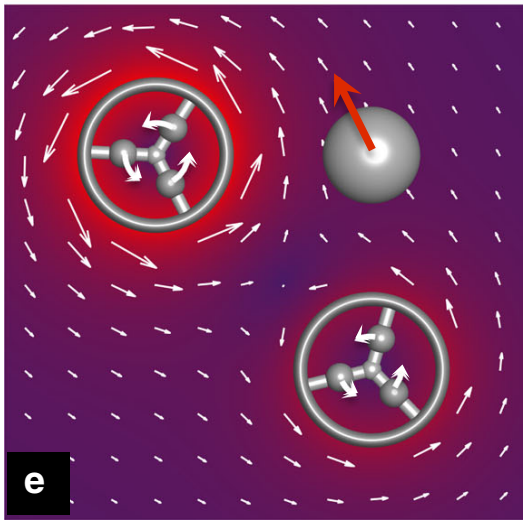


Optically driven motors

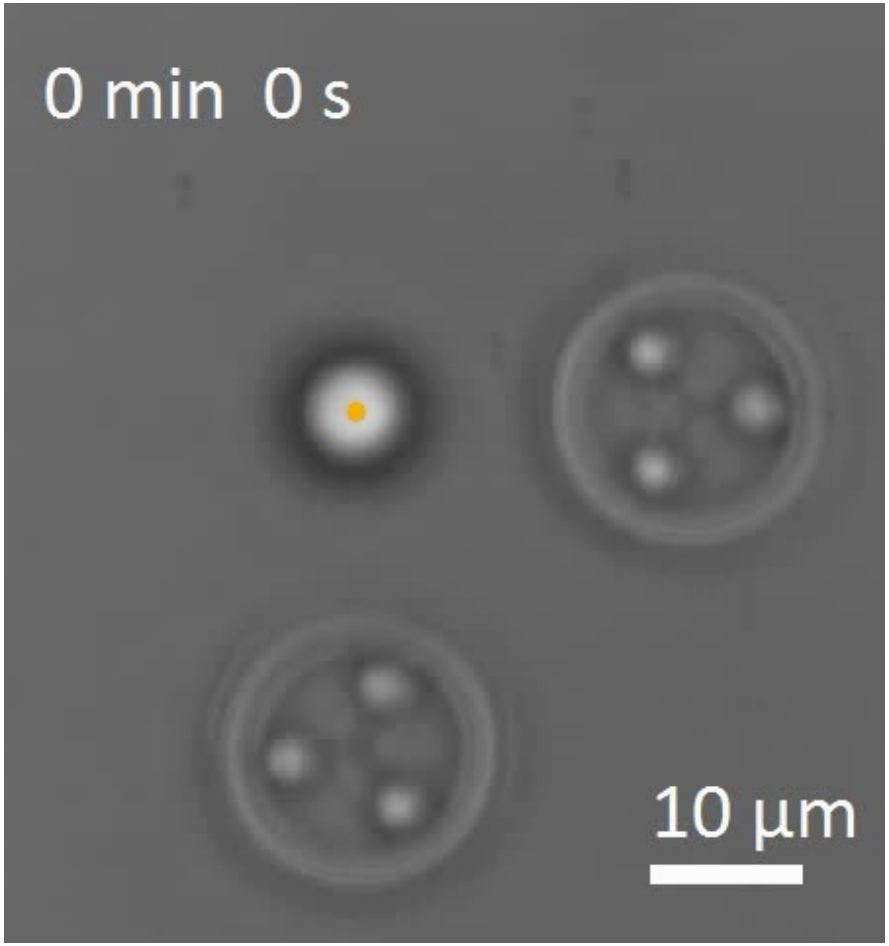
- 3D printed structures

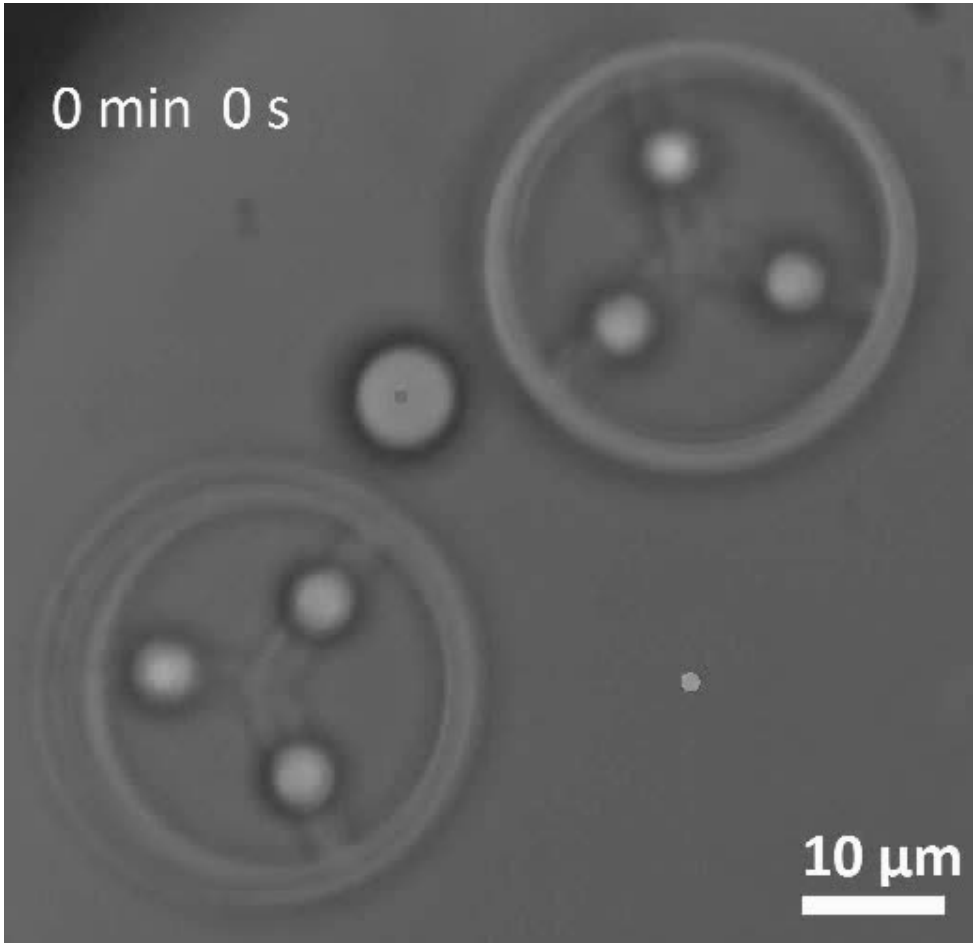




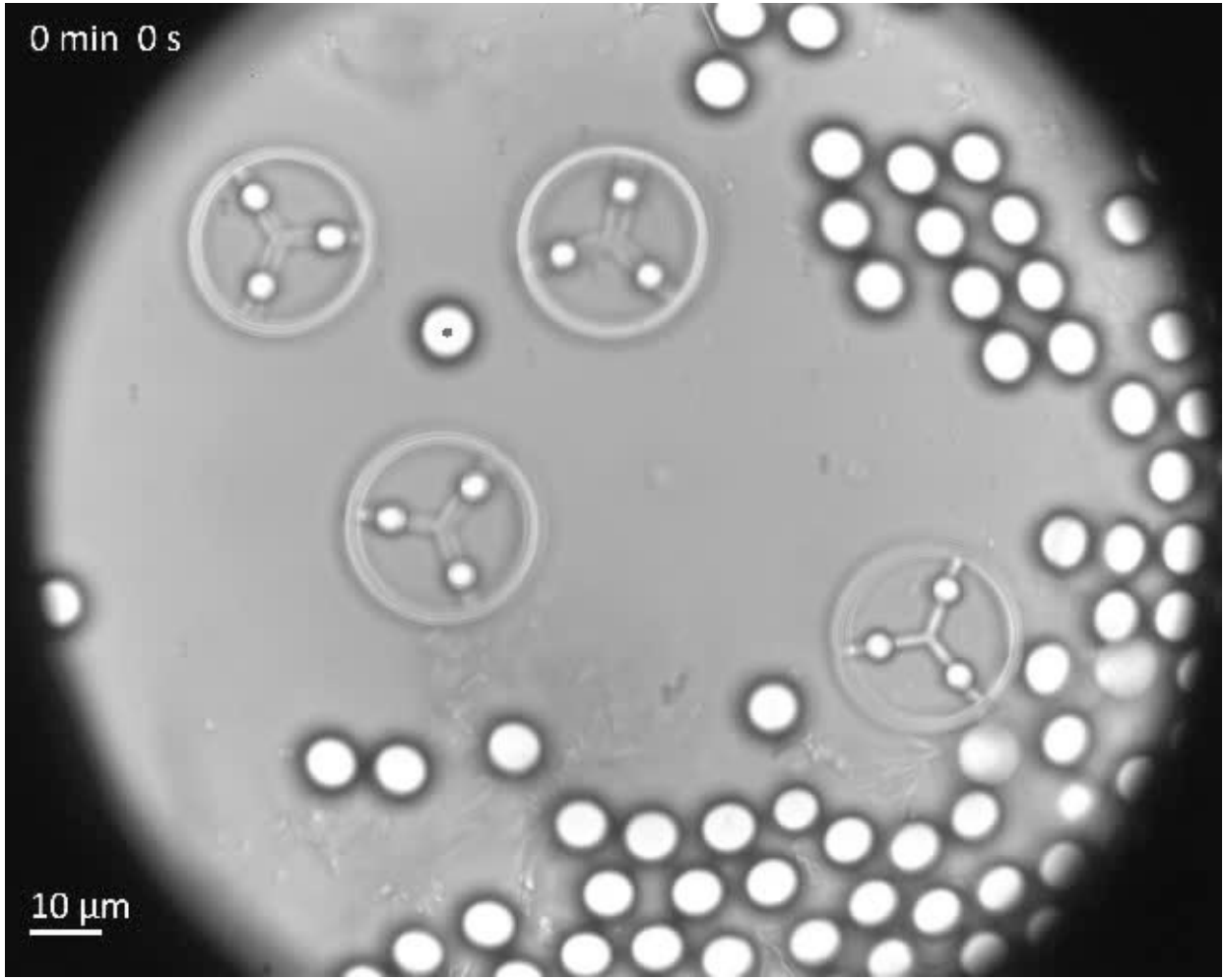


Optically driven motors



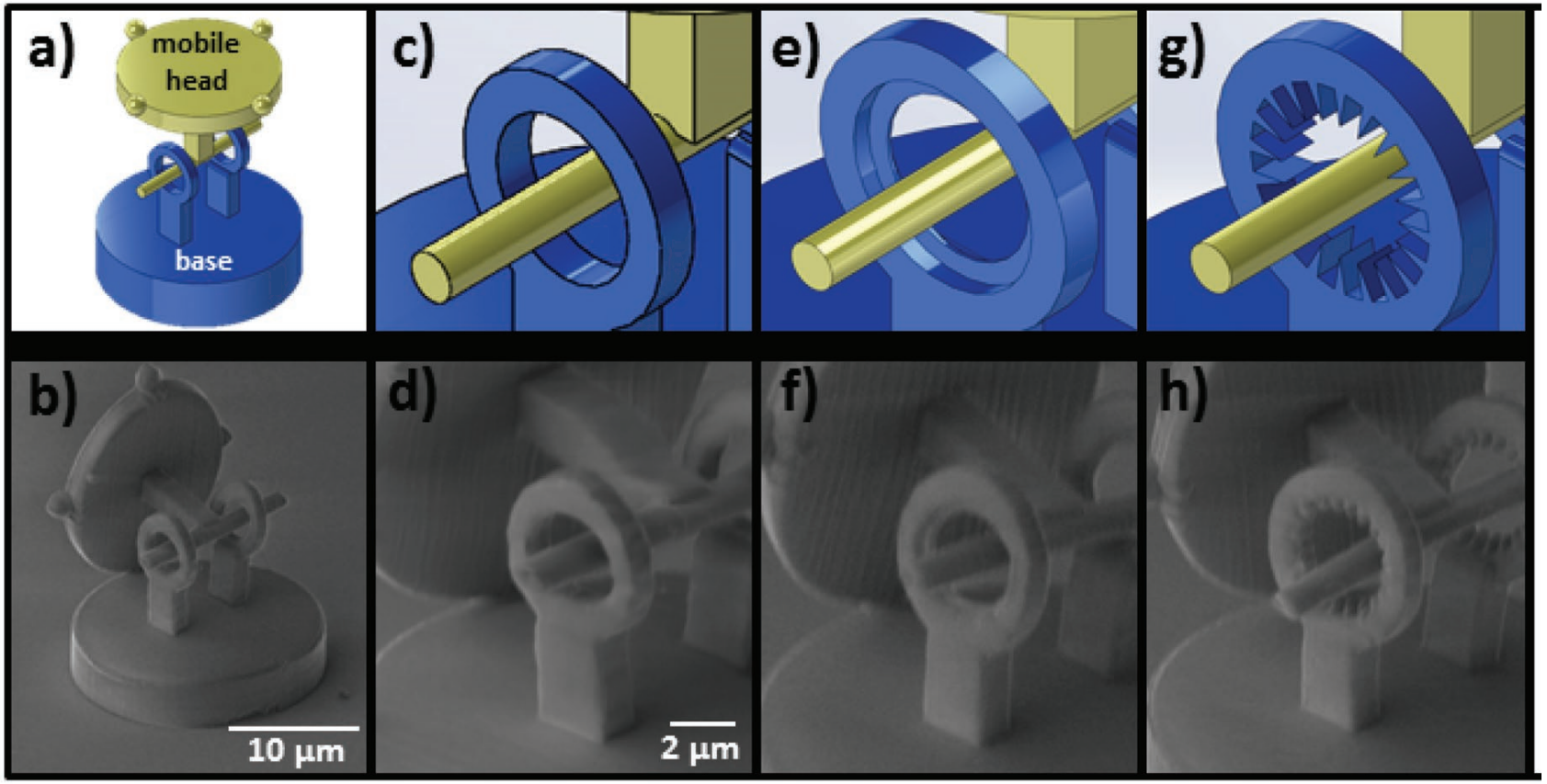


Optically driven motors



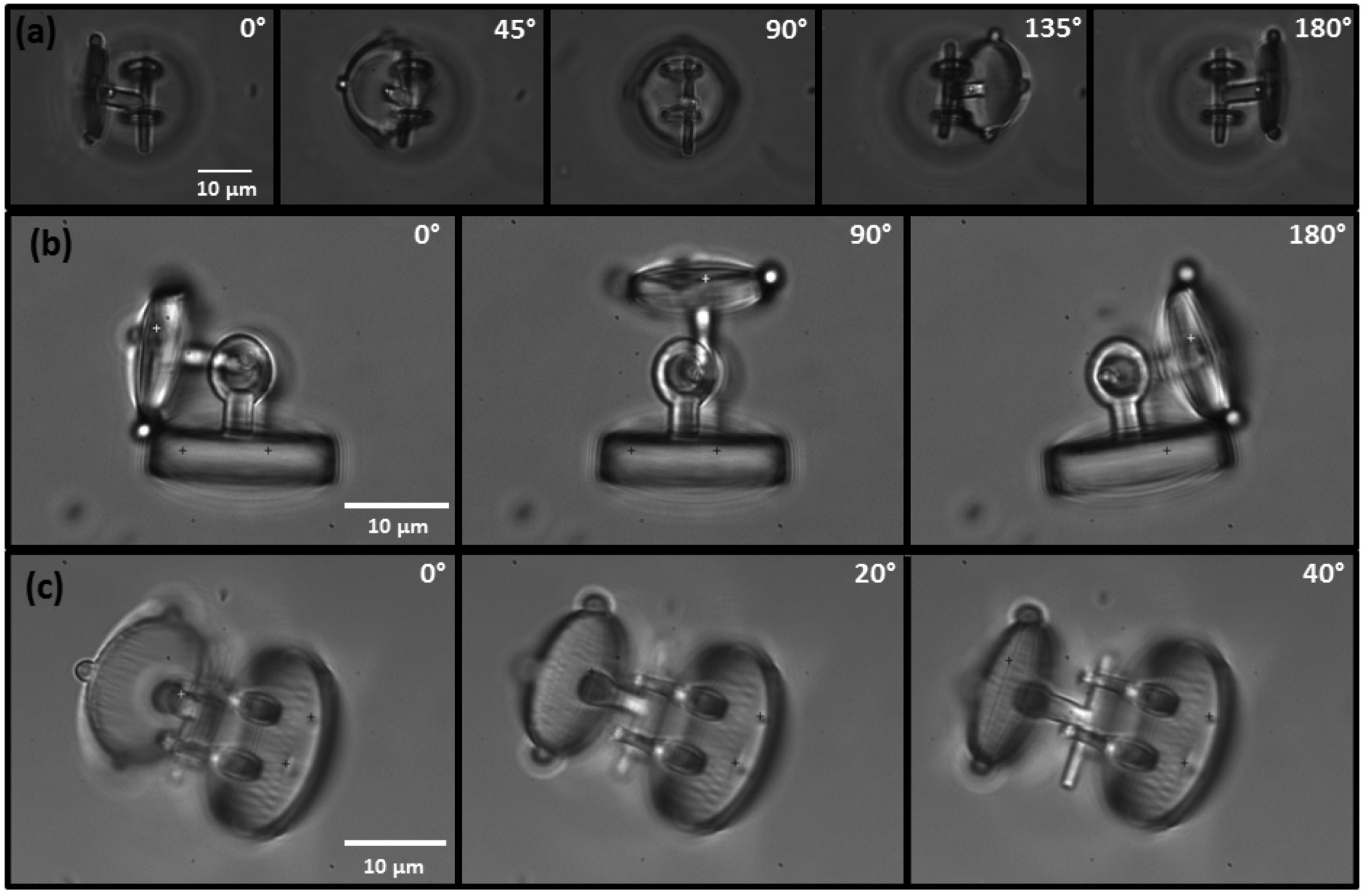
Optically driven articulated structures

- 3D printed structures



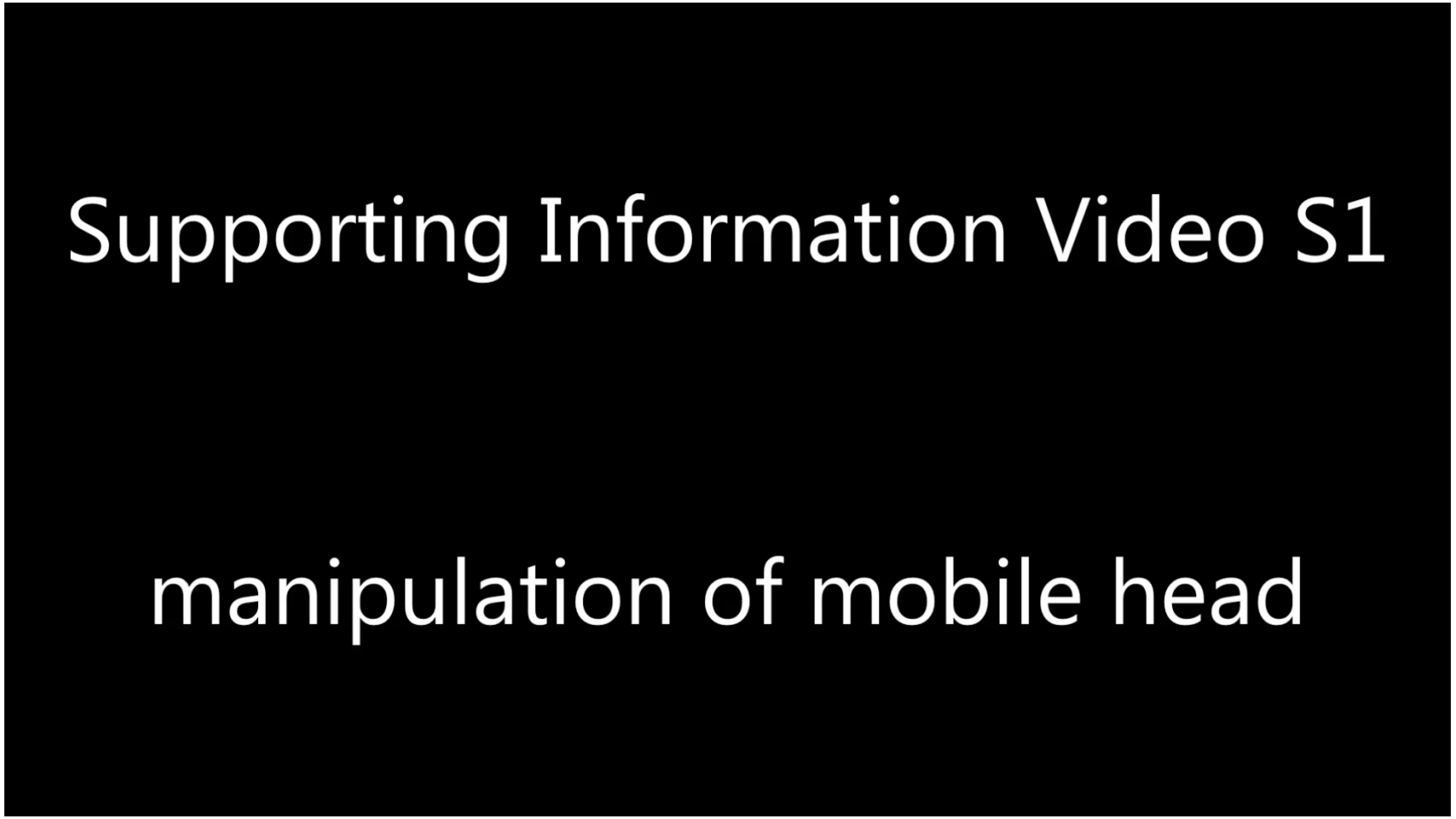
Optically driven articulated structures

- Only rotation (fixed base)
- Movement (mobile base) and rotation



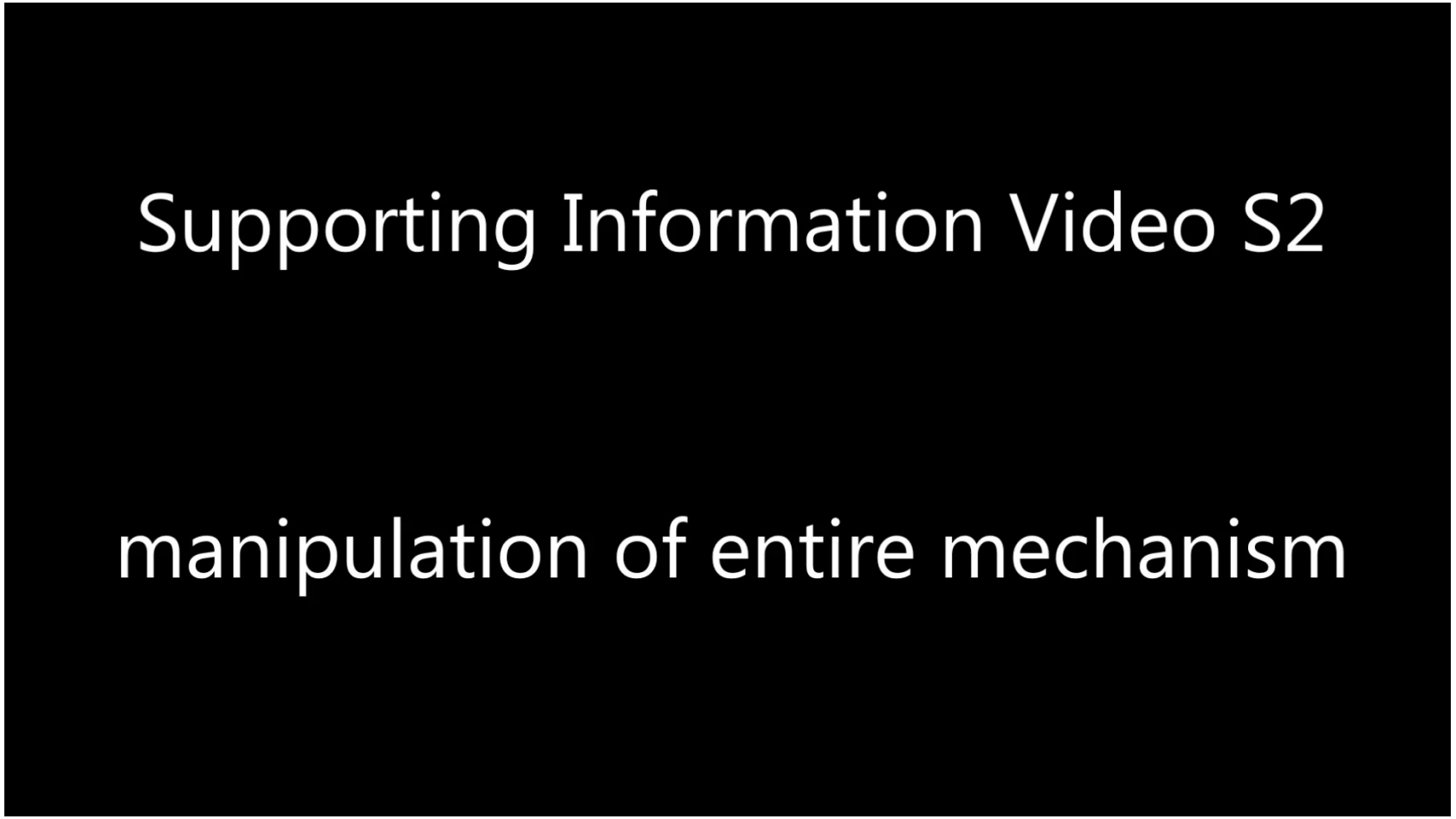
Optically driven articulated structures

- Fixed base



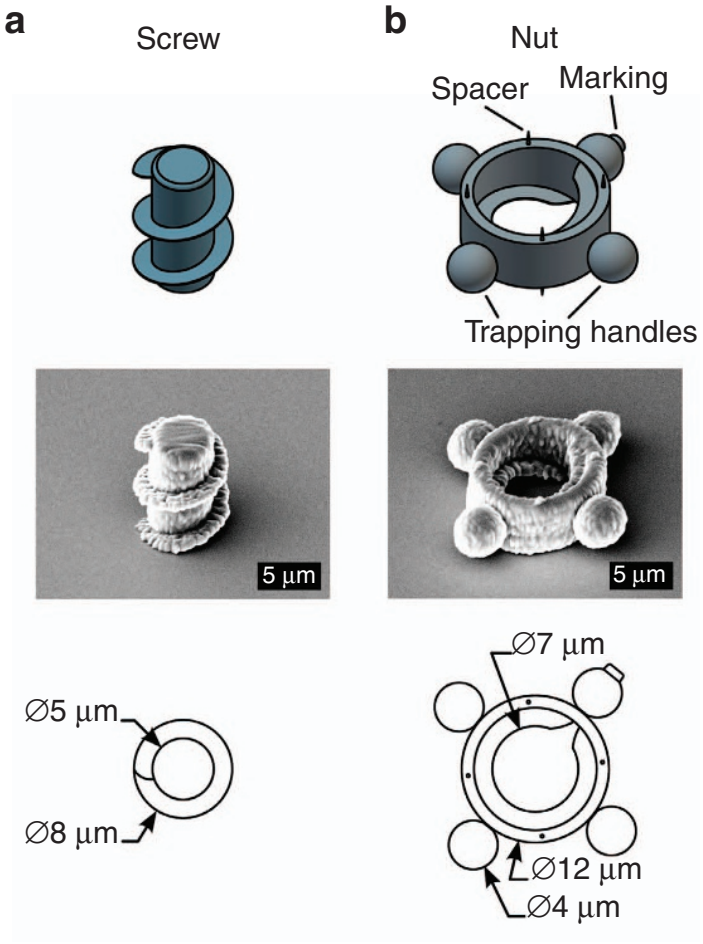
Optically driven articulated structures

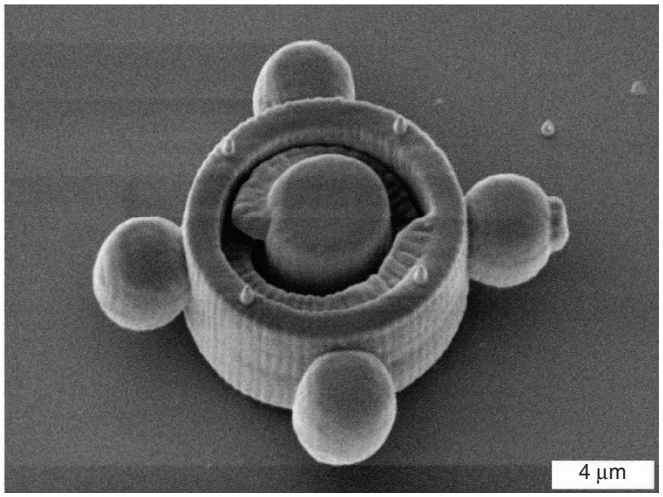
- Mobile base

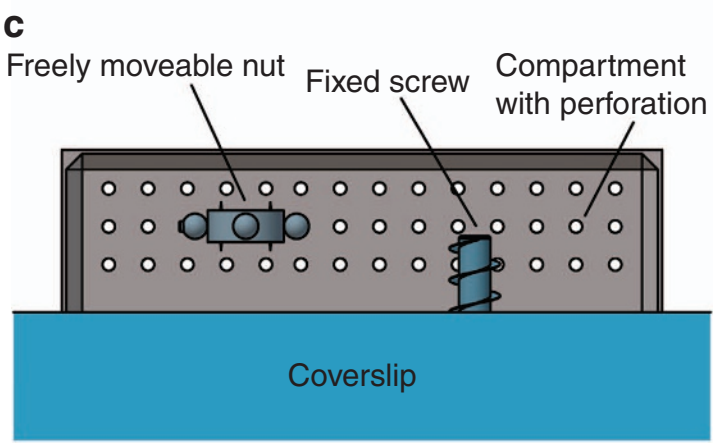


Optical screw-wrench

- Microassembly

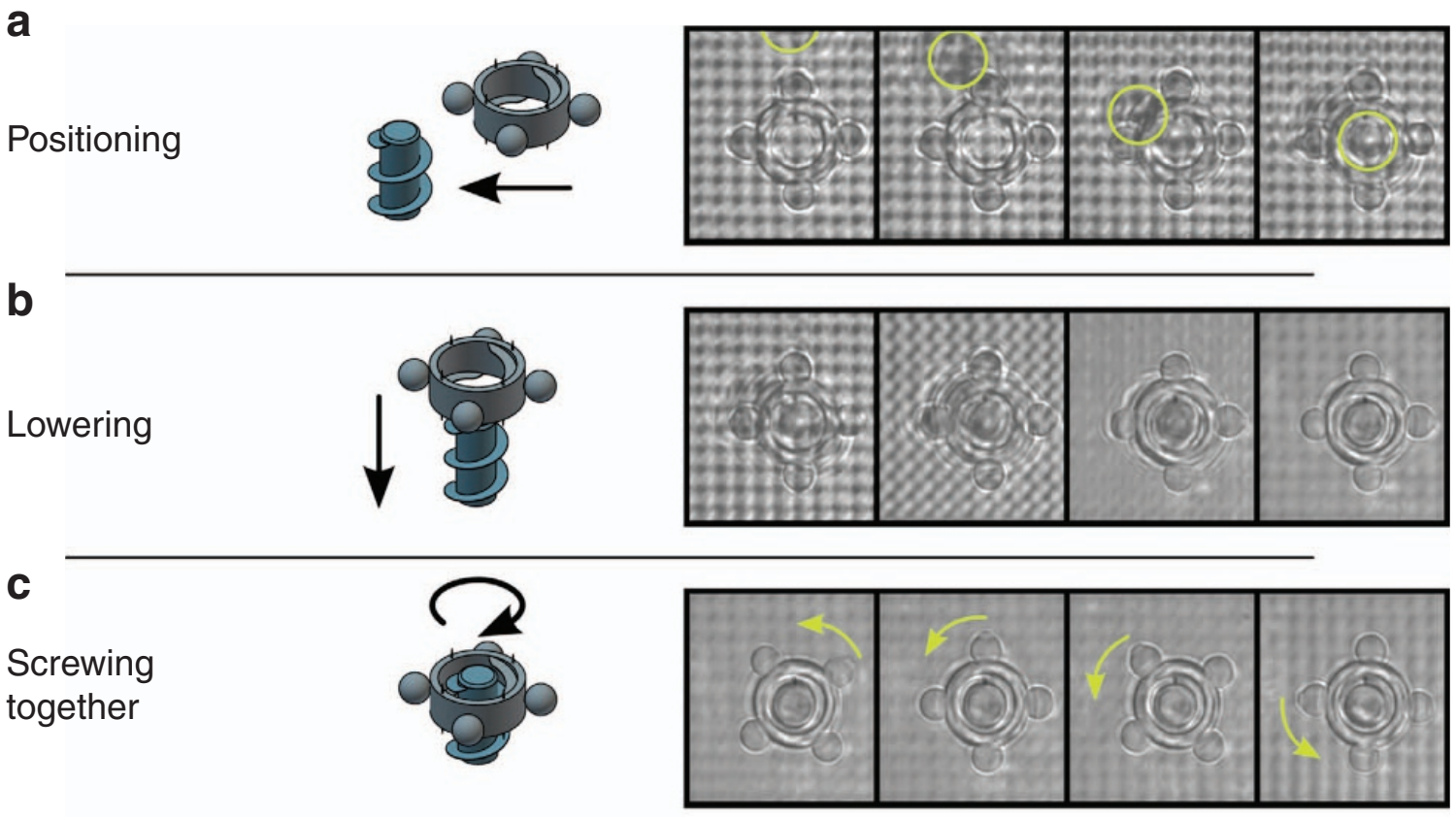






Optical screw-wrench

- Microassembly



Optical screw-wrench

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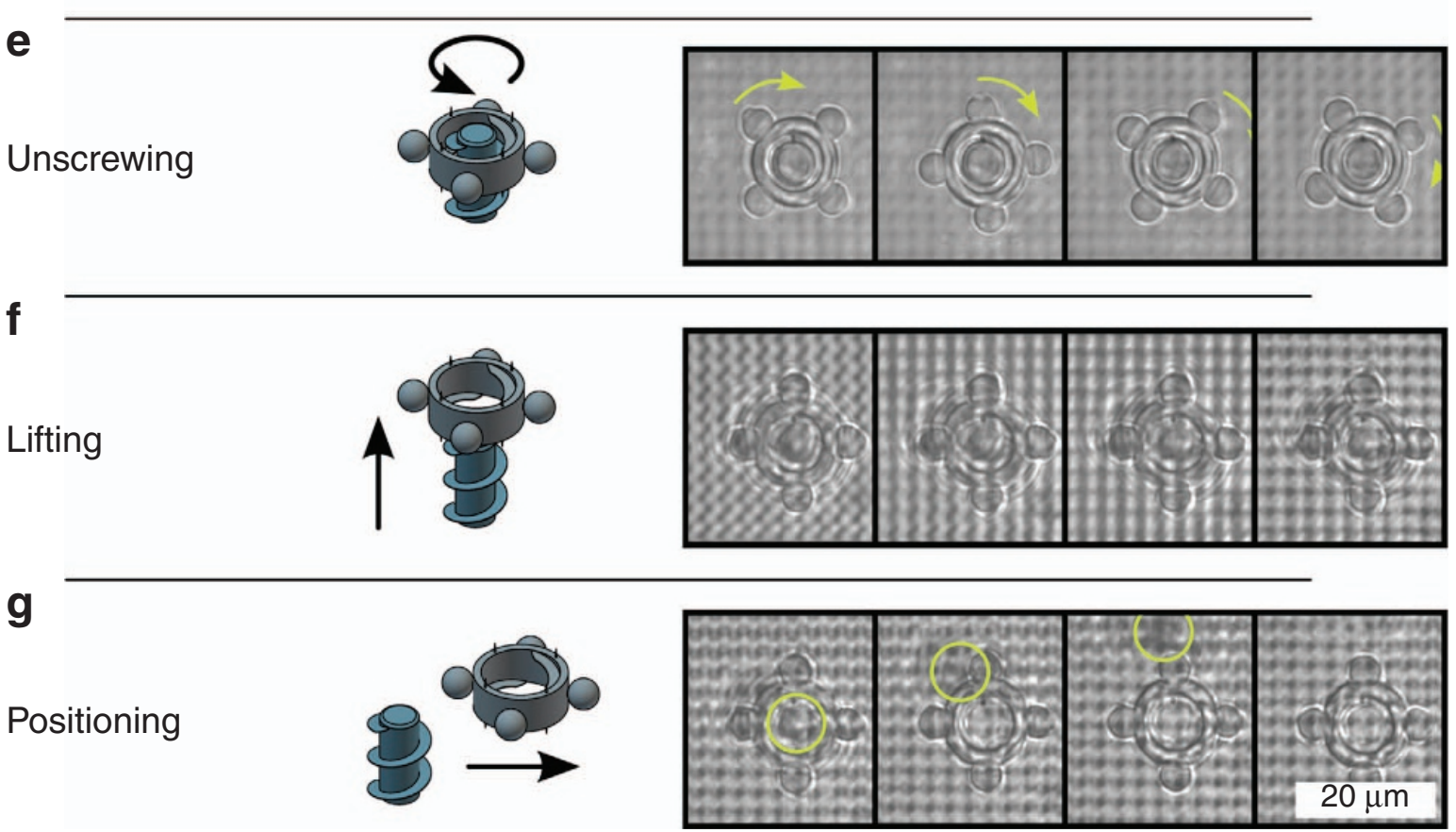


Optical reaction turbine

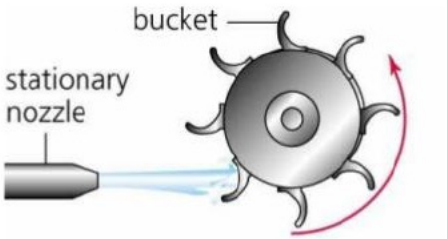
- Exploiting light's momentum to generate torque

$$T_z = \frac{Pn}{c}\left(k_\phi^{\text{out}} r^{\text{out}} - k_\phi^{\text{in}} r^{\text{in}}\right)$$

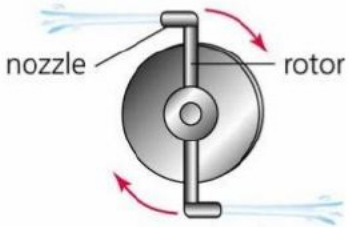
where P is the optical power, n is the refractive index of the surrounding medium, z is the direction of the rotor axis, ϕ the azimuthal coordinate, k_ϕ^{in} and k_ϕ^{out} the azimuthal components of respectively incoming and outgoing light directions and r^{in} and r^{out} the radial distances of inlet and outlet (Fig. 1a). Equation (1) is formally very similar to the Euler turbomachine equation[1] expressing torque in hydraulic turbines and where P is replaced by mass flow and nk_ϕ^{in}/c, nk_ϕ^{out}/c by the azimuthal components of inlet and outlet velocities.

Optical reaction turbine

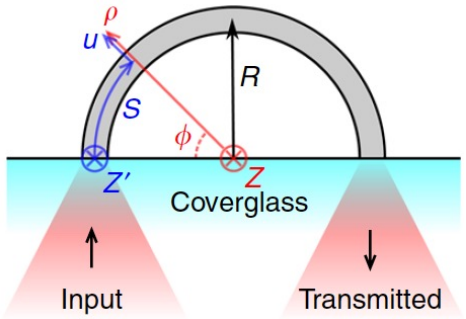
- Design to optimize momentum transfer (garden sprinkler)

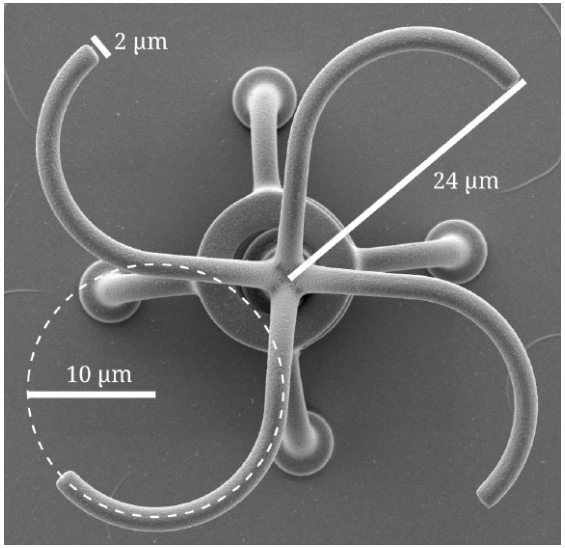


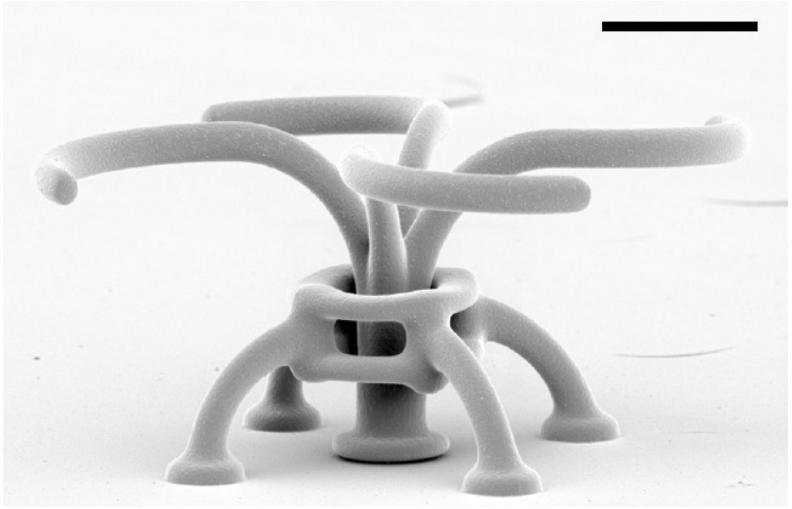
Impulse Turbine



Reaction Turbine

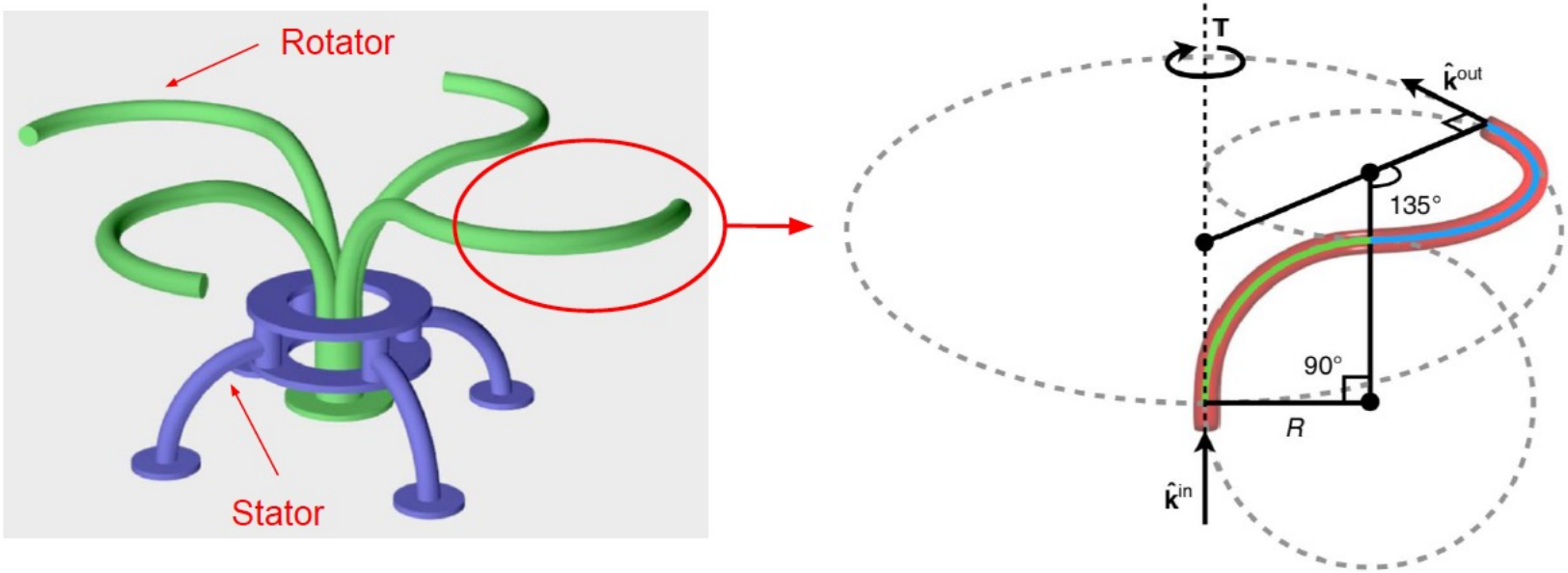




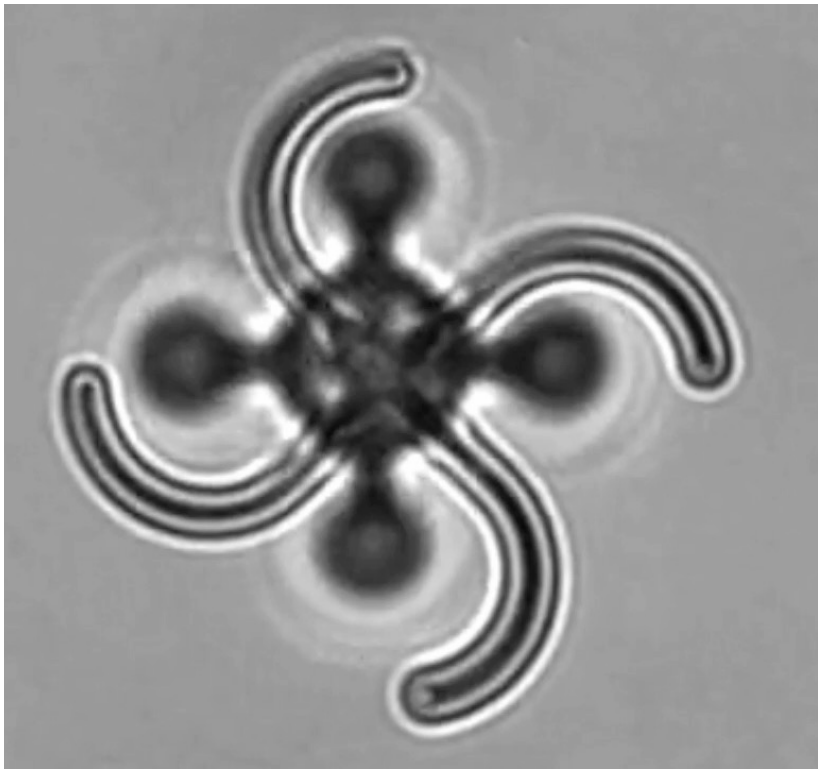


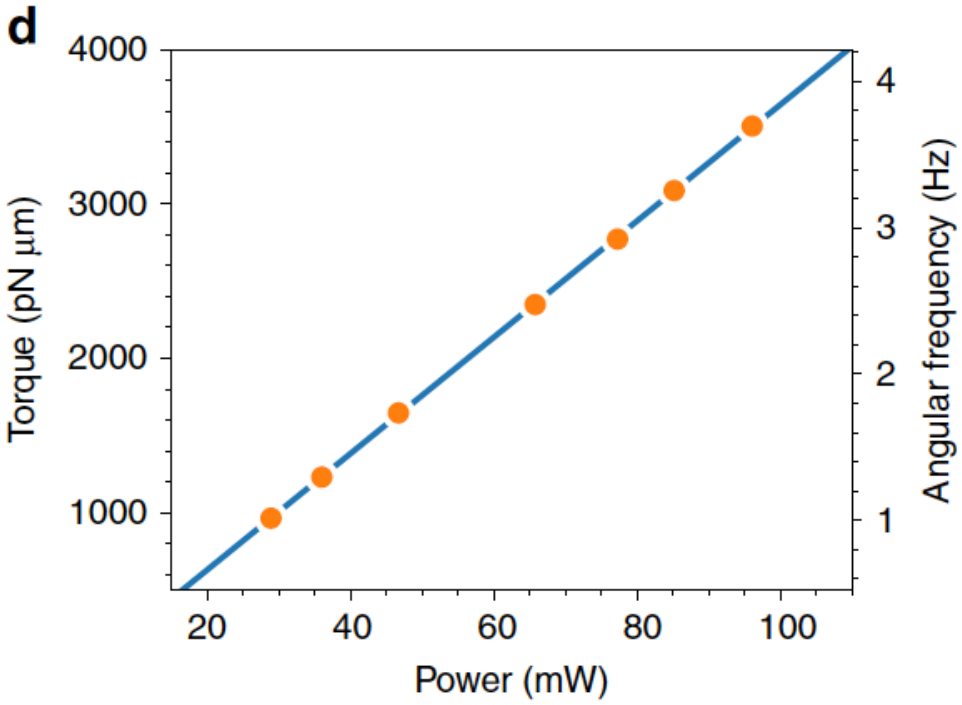
Optical reaction turbine

- Guided propagation of light
- Maximize reaction torque while minimizing losses due to bending of the structure
- Source of losses: coupling, splitting, bending



Optical reaction turbine



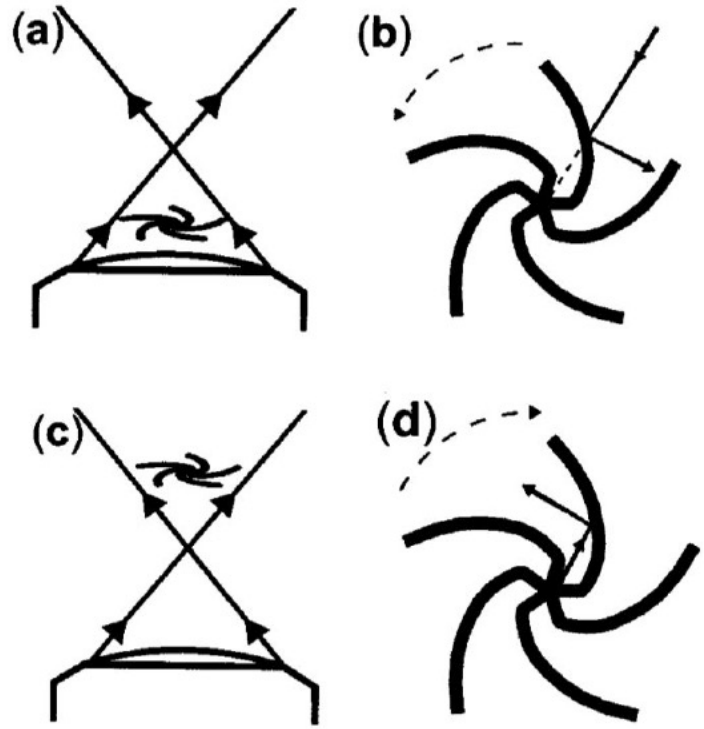


Optical impulse turbine (light mill)

- Optical tweezers and radiation force
- Torque is induced by the scattering of light on an anisotropic object

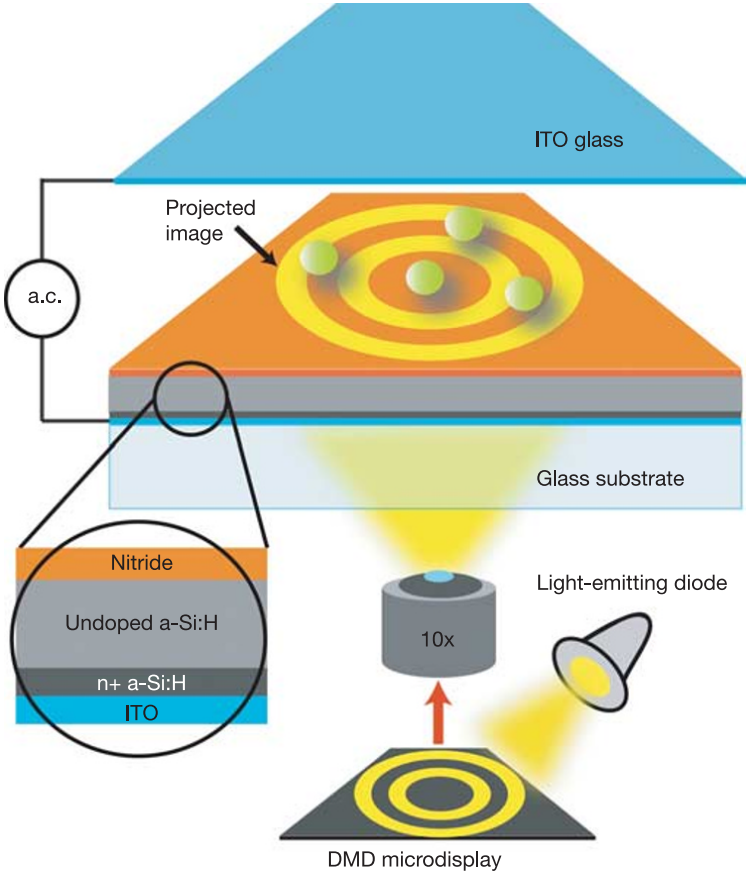
The light beam

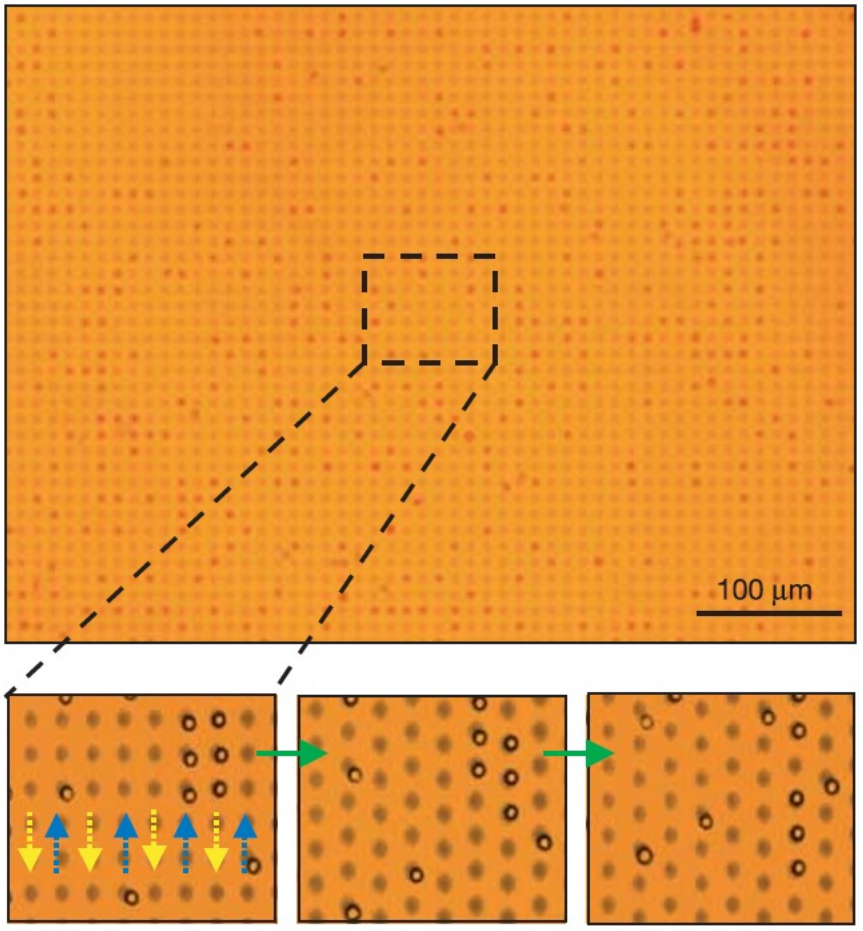
- Below the focal plane, has large forces pointing toward axis
- Above the focal plane, the forces are pointing away from the axis



Optoelectronic tweezers

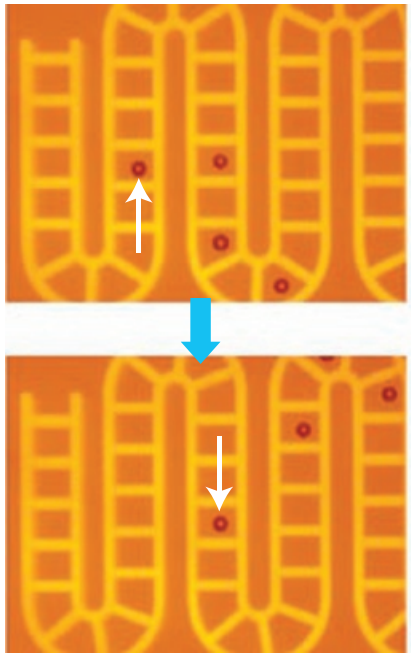
- Using projected light patterns to form virtual electrodes on a photosensitive substrate

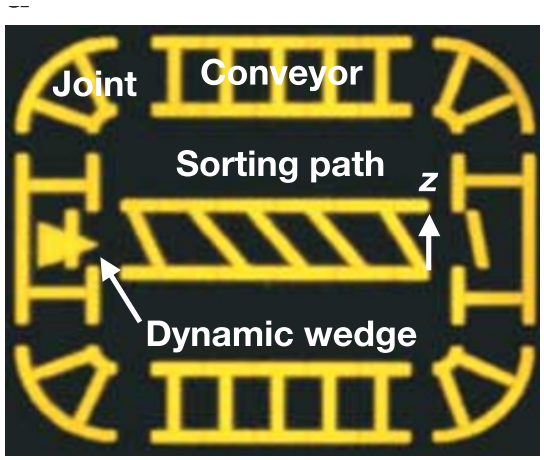


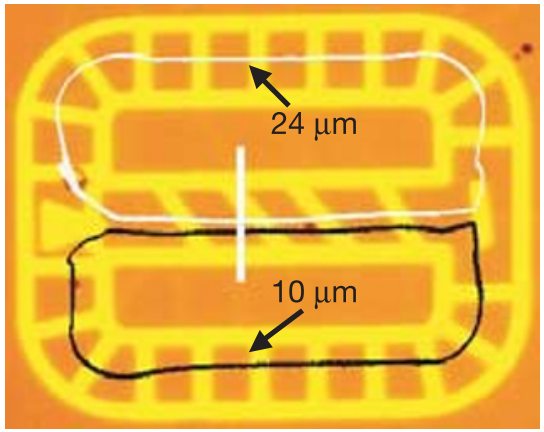


Optoelectronic tweezers

- High-resolution dielectrophoresis (DEP) electrodes
- Induced dipoles in particles subjected to non-uniform electric field
- Electric field gradient and polarizability of the particle
  - Dielectric properties of the particle and the medium





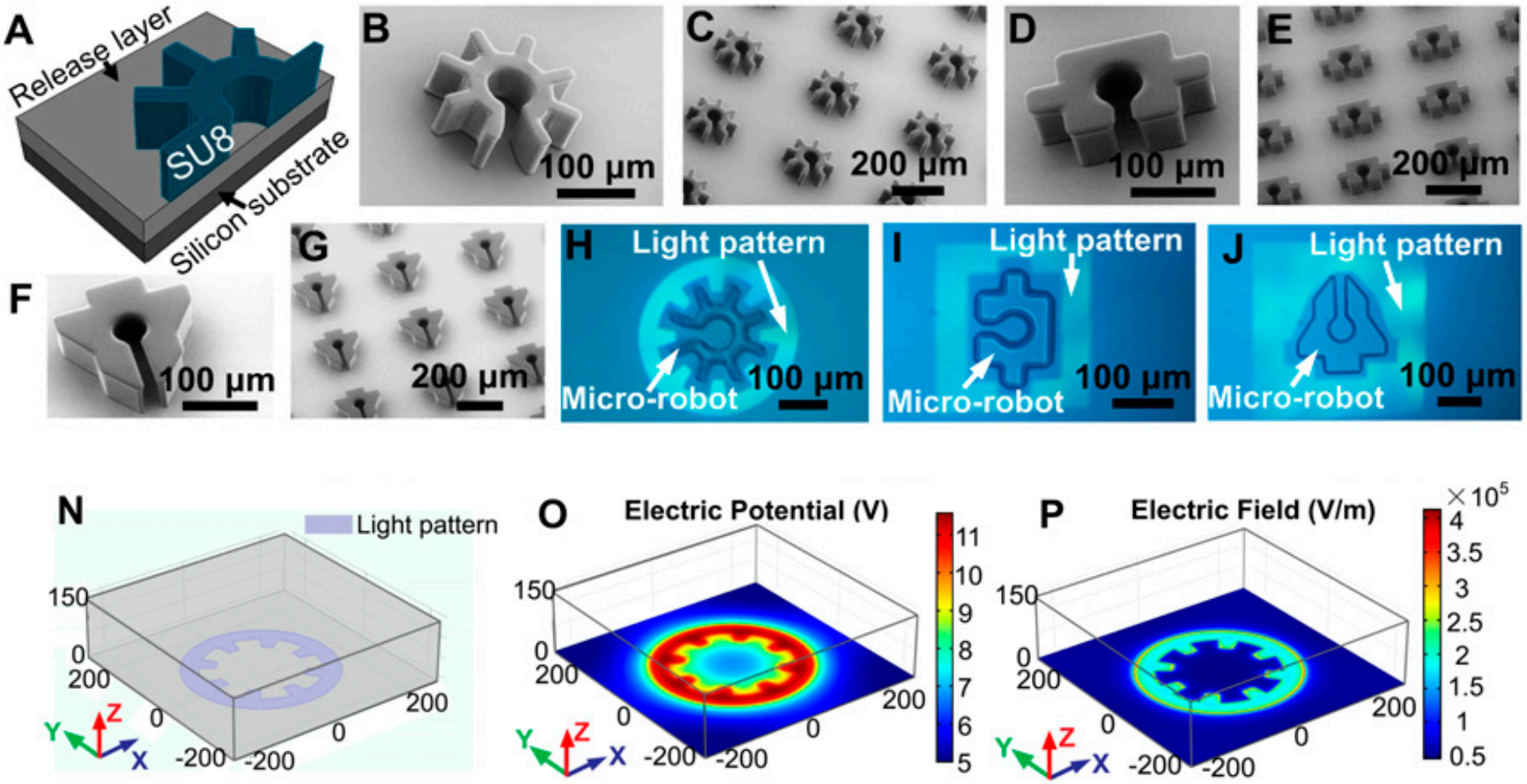


Optoelectronic tweezers

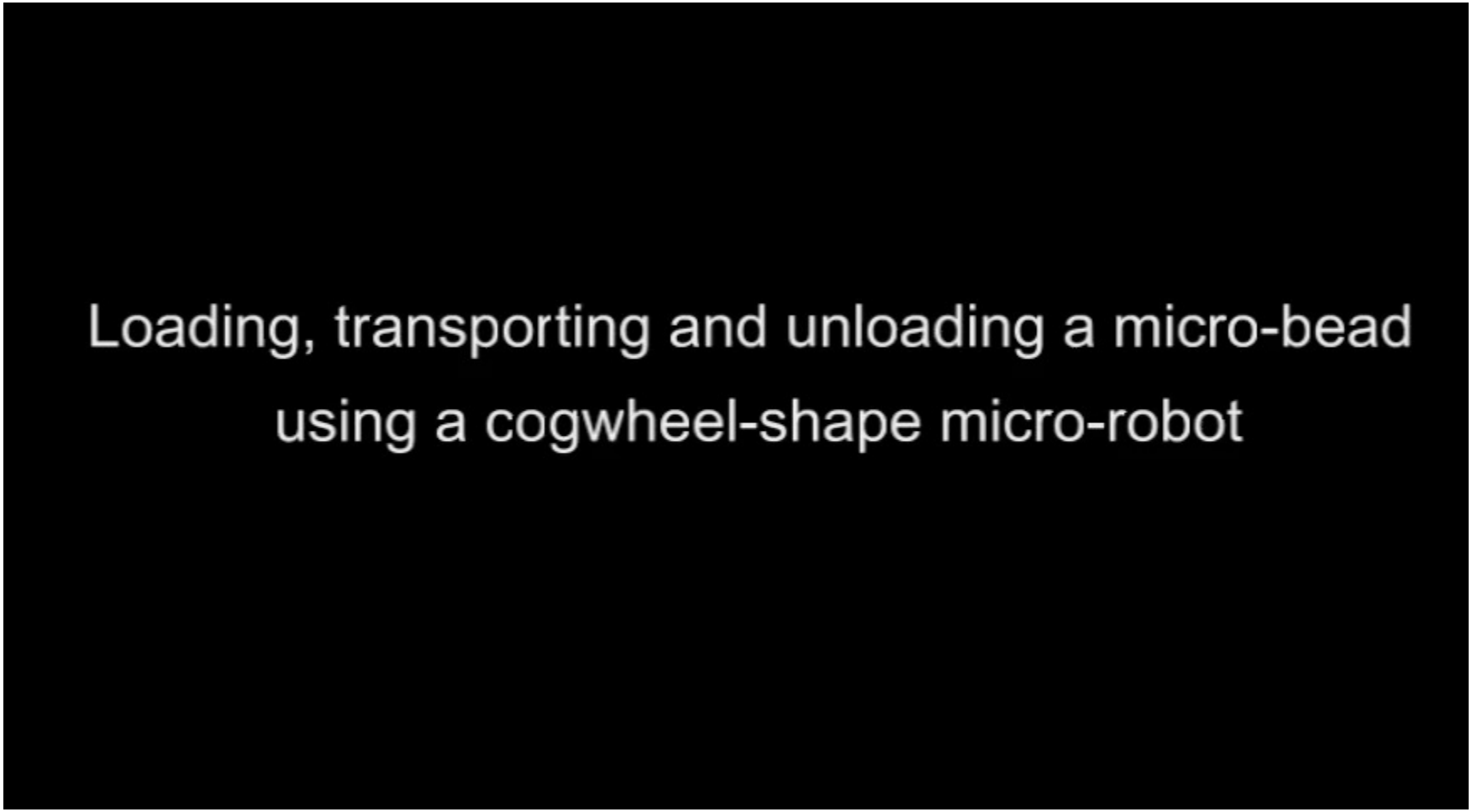
- Low voltage: 10 V peak-to peak
- Optical intensity: 10 nW/μm^2
  - 100,000 times lower than that used in optical tweezers
- Pixel size: 1.52 μm with 10X objective
- 1 mW output power 625 nm laser: 40,000 pixels
- 1 mm x 1 mm manipulation area
  - 500 times larger than that of optical tweezers

Optoelectronic microrobot

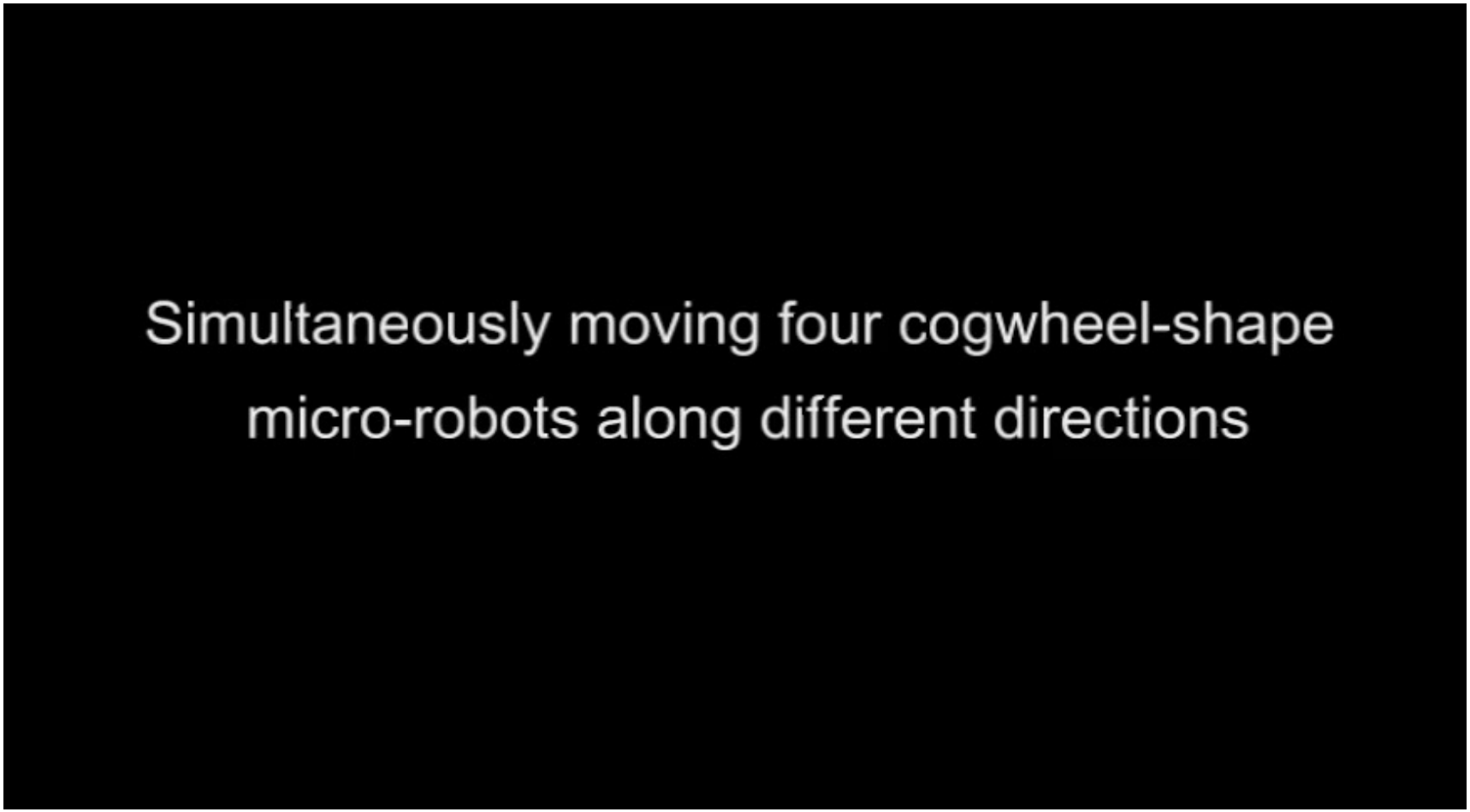
- Negative DEP force to hold microfabricated objects



Optoelectronic microrobot

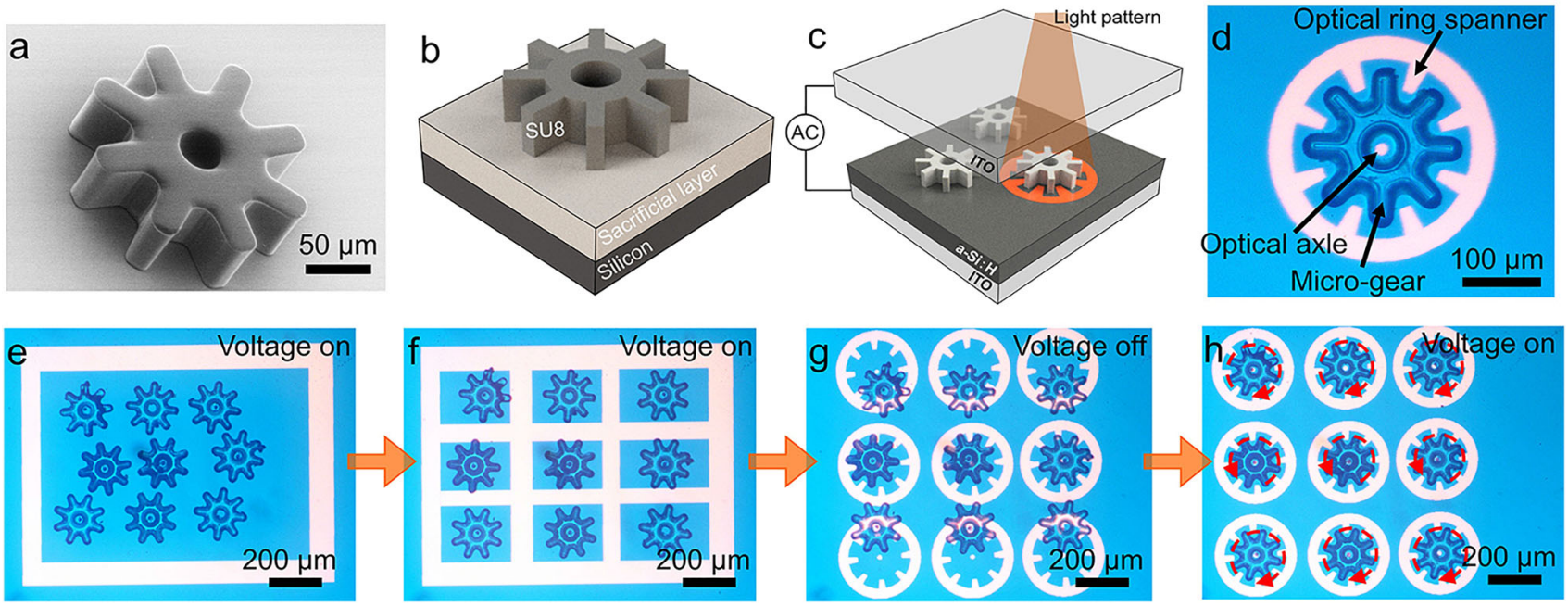


Optoelectronic microrobot

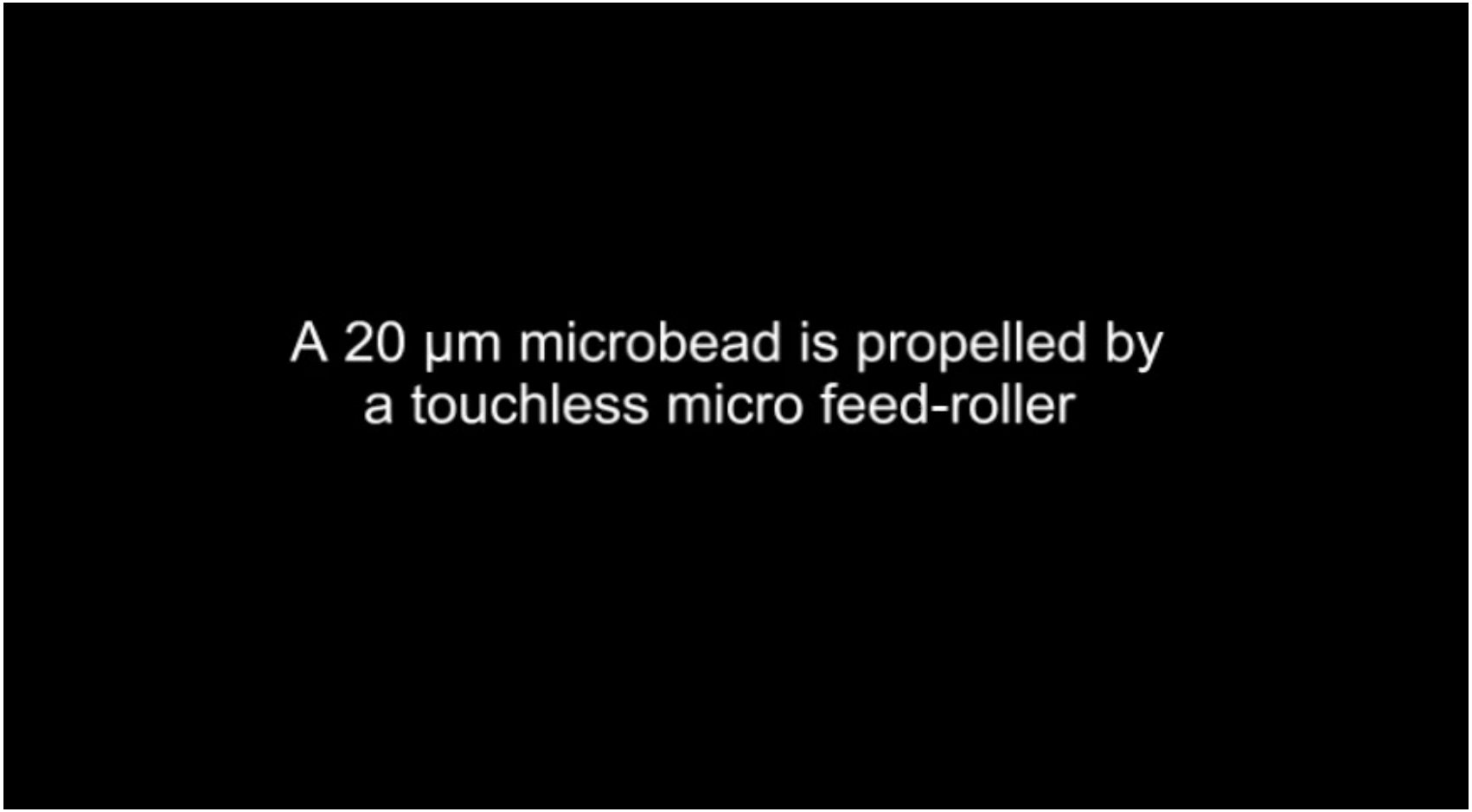


Optoelectronic microrobot

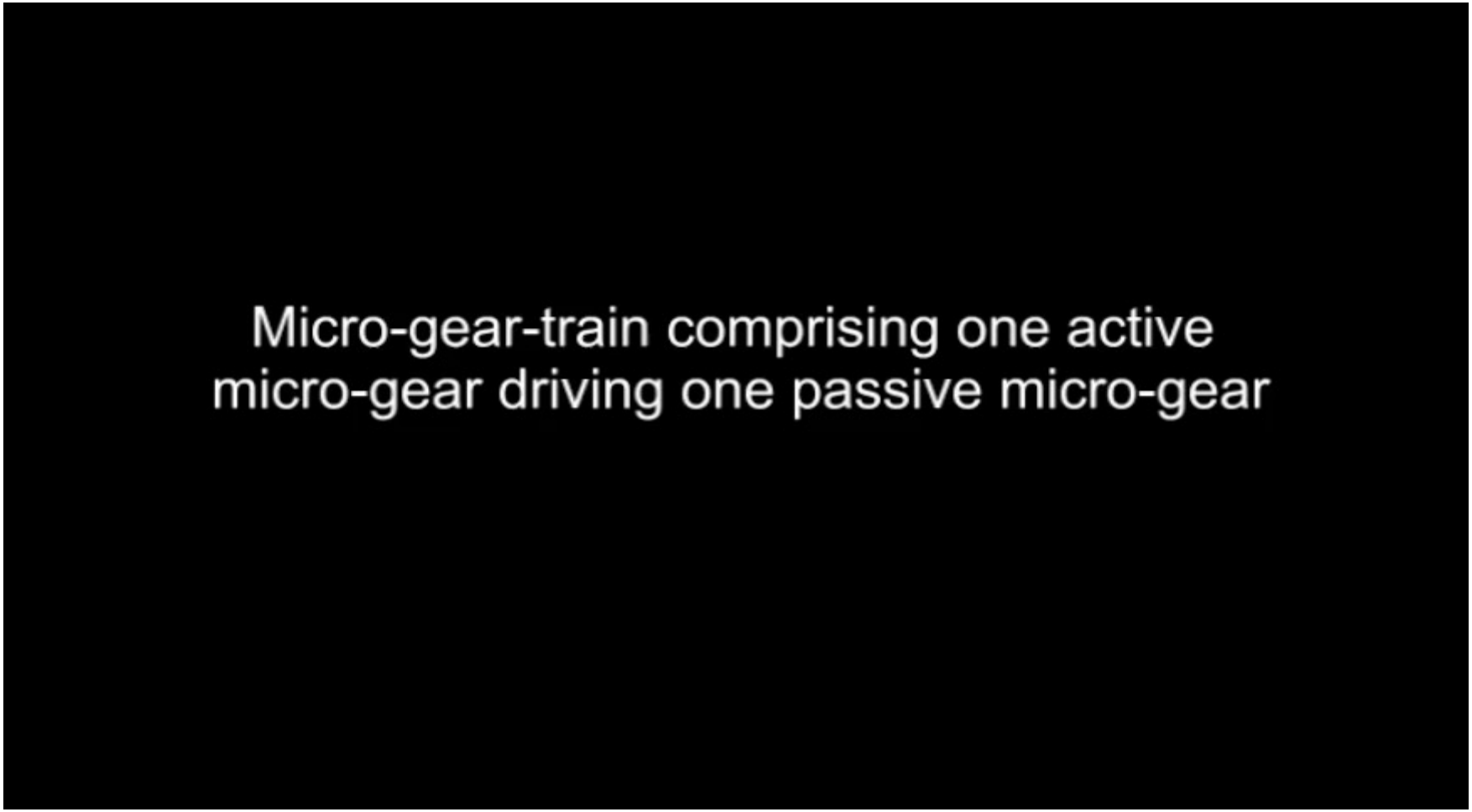
- Micromotors and compound mechanisms



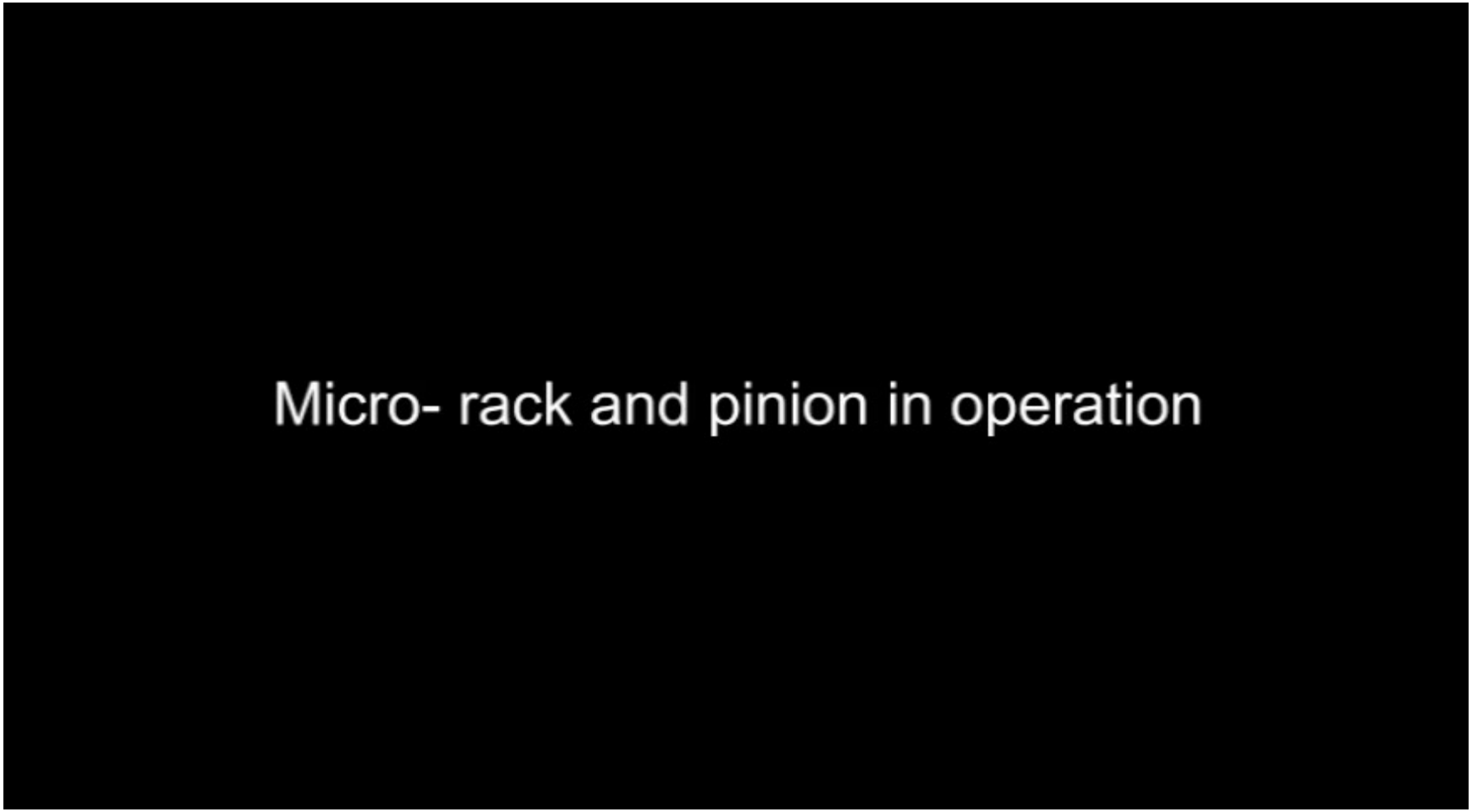
Optoelectronic microrobot



Optoelectronic microrobot

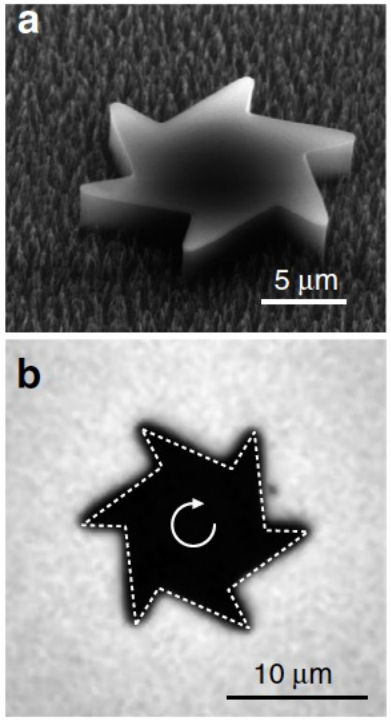


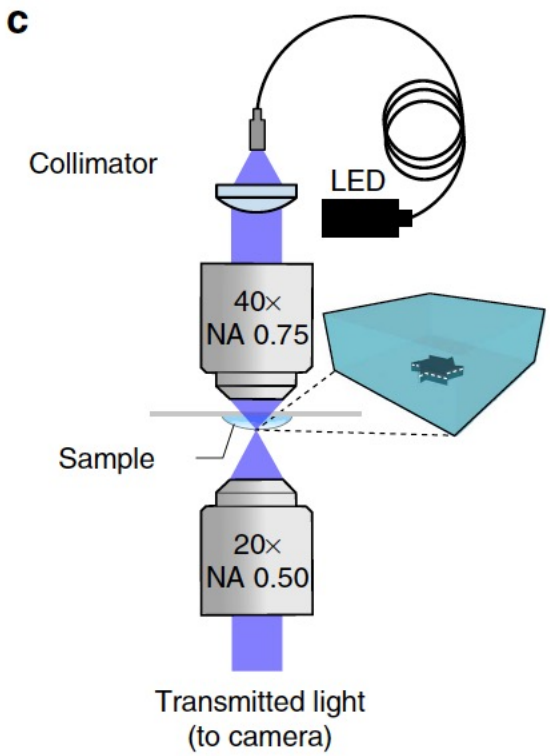
Optoelectronic microrobot

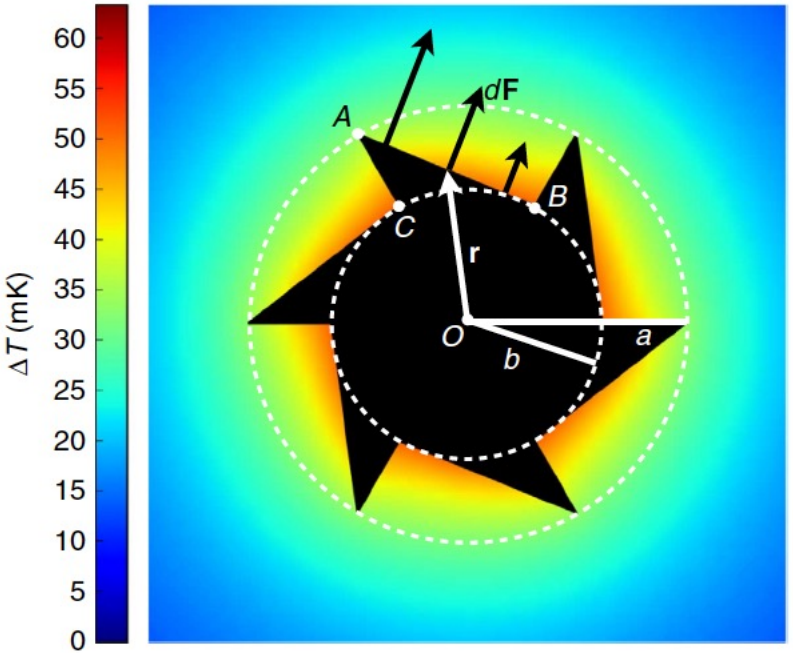


Thermocapillary Forces

- Microgear at the liquid-air interface
- Carbon coating to increase absorption
- Marangoni effect

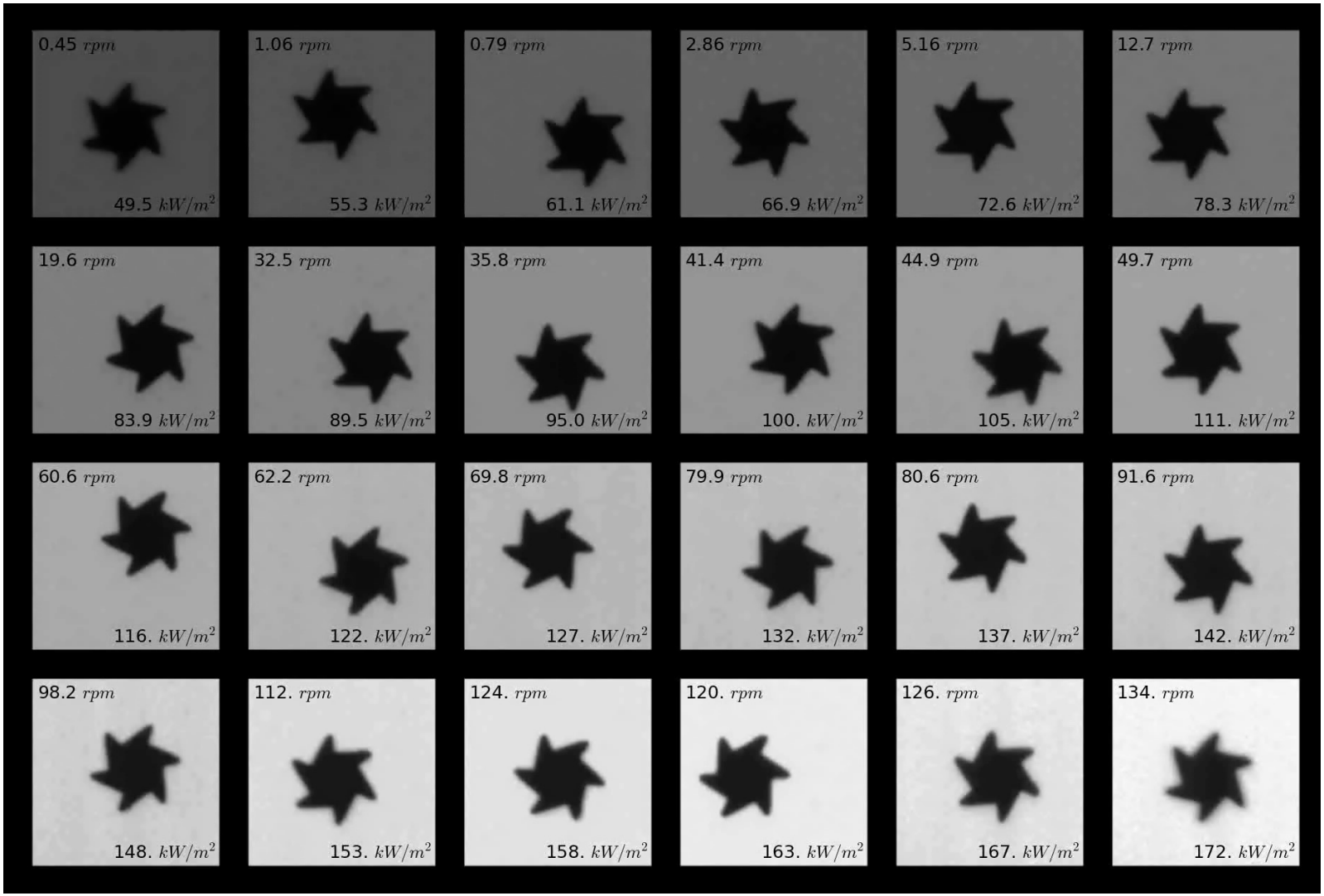






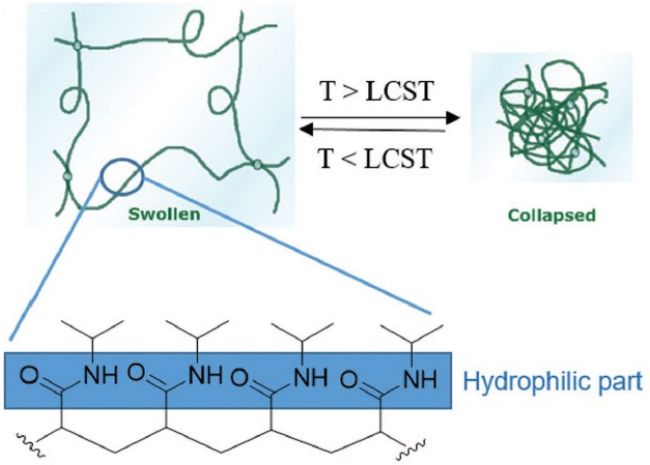
$$\boldsymbol{\tau} = \int \mathbf{r} \times d\mathbf{F} = \int \mathbf{r} \times \hat{n}\, \gamma(T)\, ds,$$

Thermocapillary Forces



Smart hydrogels

- Gels made of networks of cross-linked long polymer chains
- Soft material: Young's modulus in the kPa range
- Absorb-repel water in response to an external stimulus (swelling)
  - Temperature, pH, chemicals



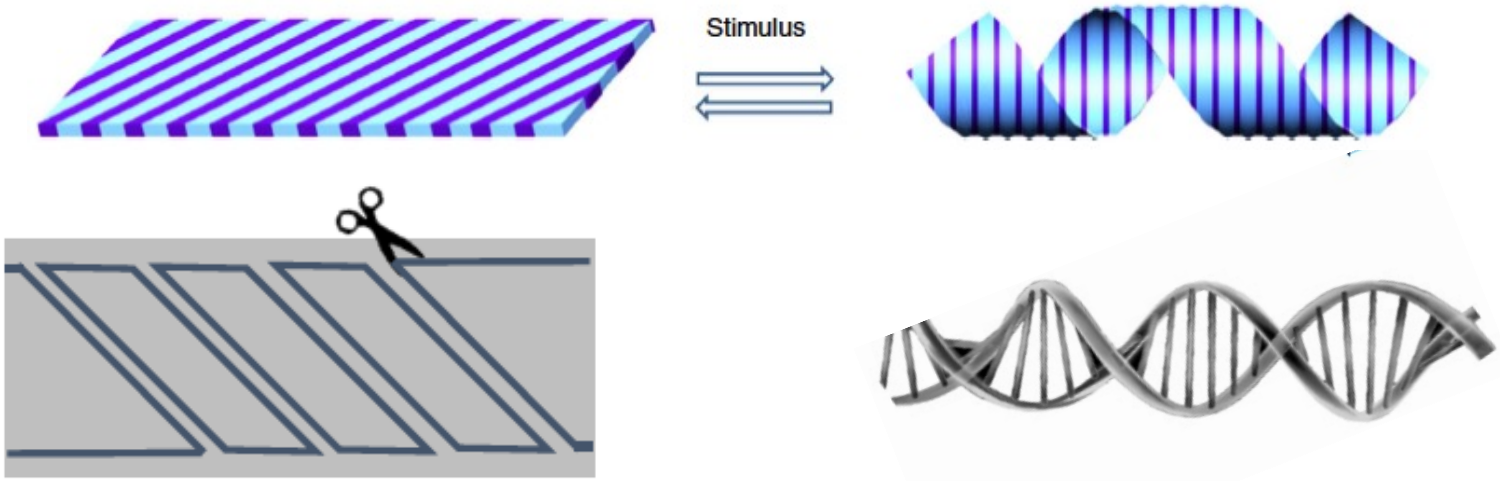
- Relatively small forces but high volumetric change
  - Energy densities up to 460 kJ m^{-3}
  - Strains of up to 90% under 4 MPa load
  - Can be stretched up to 1200%
  - Response is diffusion limited: millimeter sized gels ~seconds
  - Chemical stability and performance degradation in time

Thermoresponsive Hydrogels

- Lower critical solution temperature (LCST) and upper critical solution temperature (UCST)

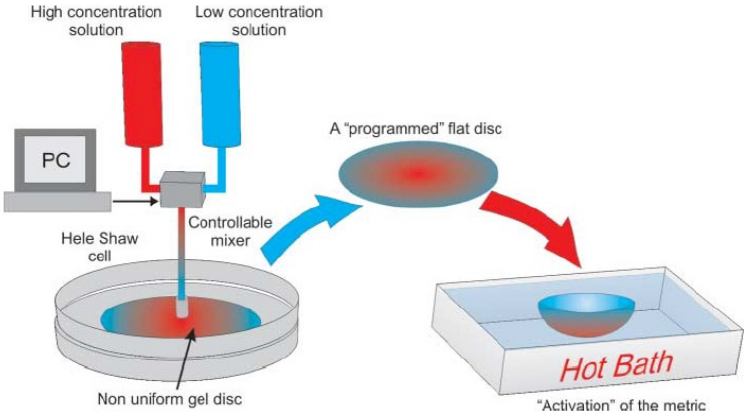
- poly(N-isopropylacrylamide) or pNIPAM: a combination of hydrophilic and hydrophobic segments in the polymer chain
  - At temperatures below LCST, swell due to domination of hydrophilic interactions with water
  - At temperature above LCST, the hydrogen bonds with water are broken and hydrophobic interactions among the polymer chains dominate, which result in deswelling

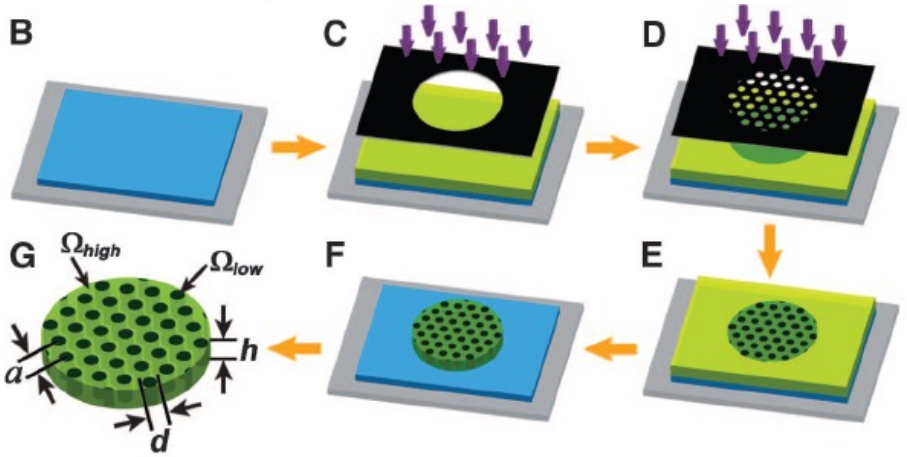
Origami and Kirigami with Hydrogels



Kim etal, *Science*, 2012

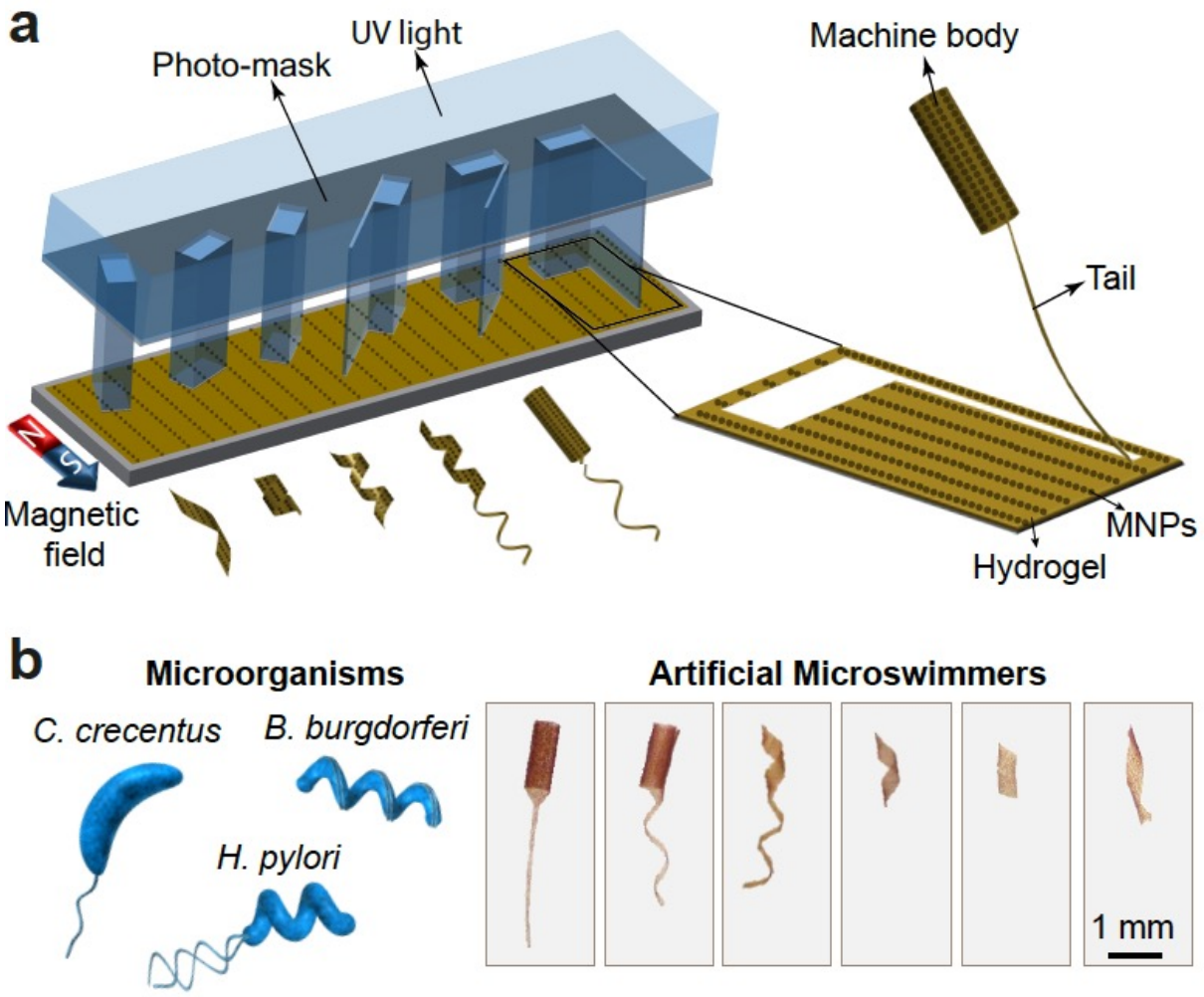
Klein etal, *Science*, 2007



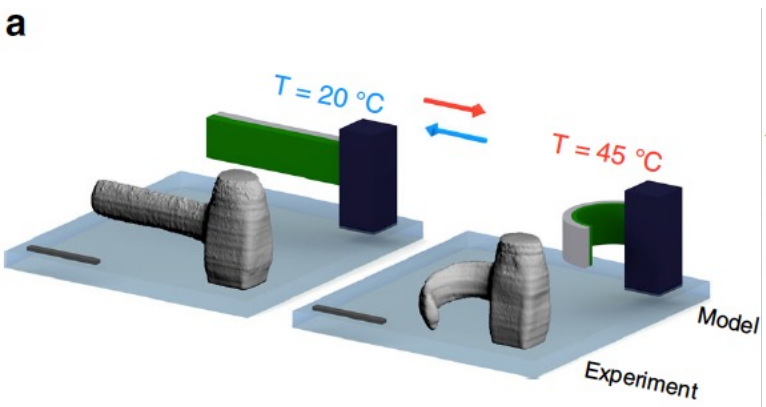


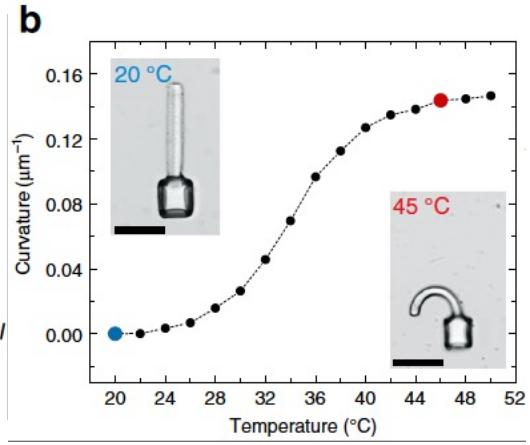
Programmable self-folding

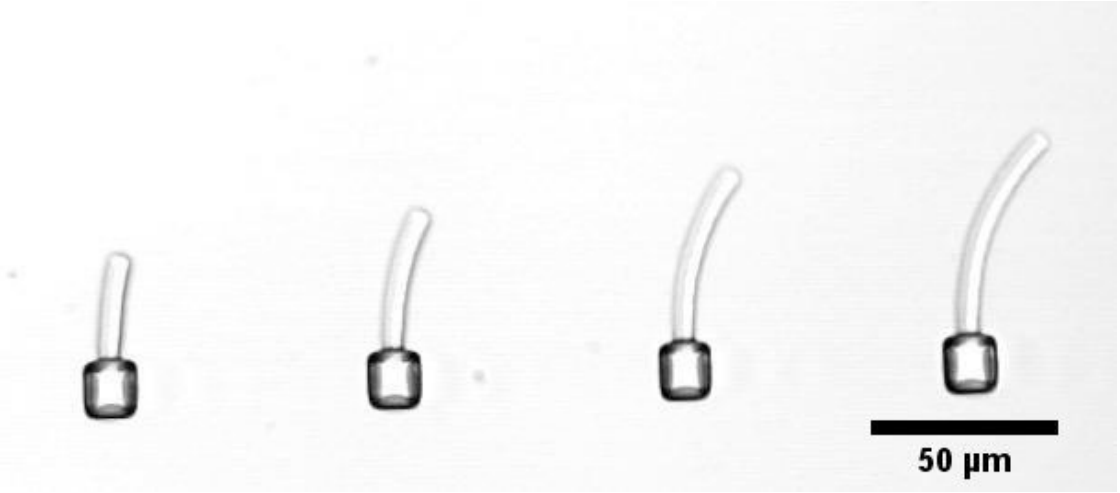
- Differential Swelling via Particle Gradients

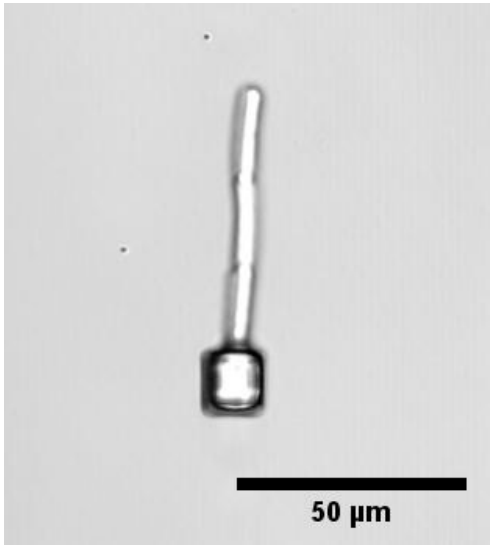


Direct Laser Writing of Actuators

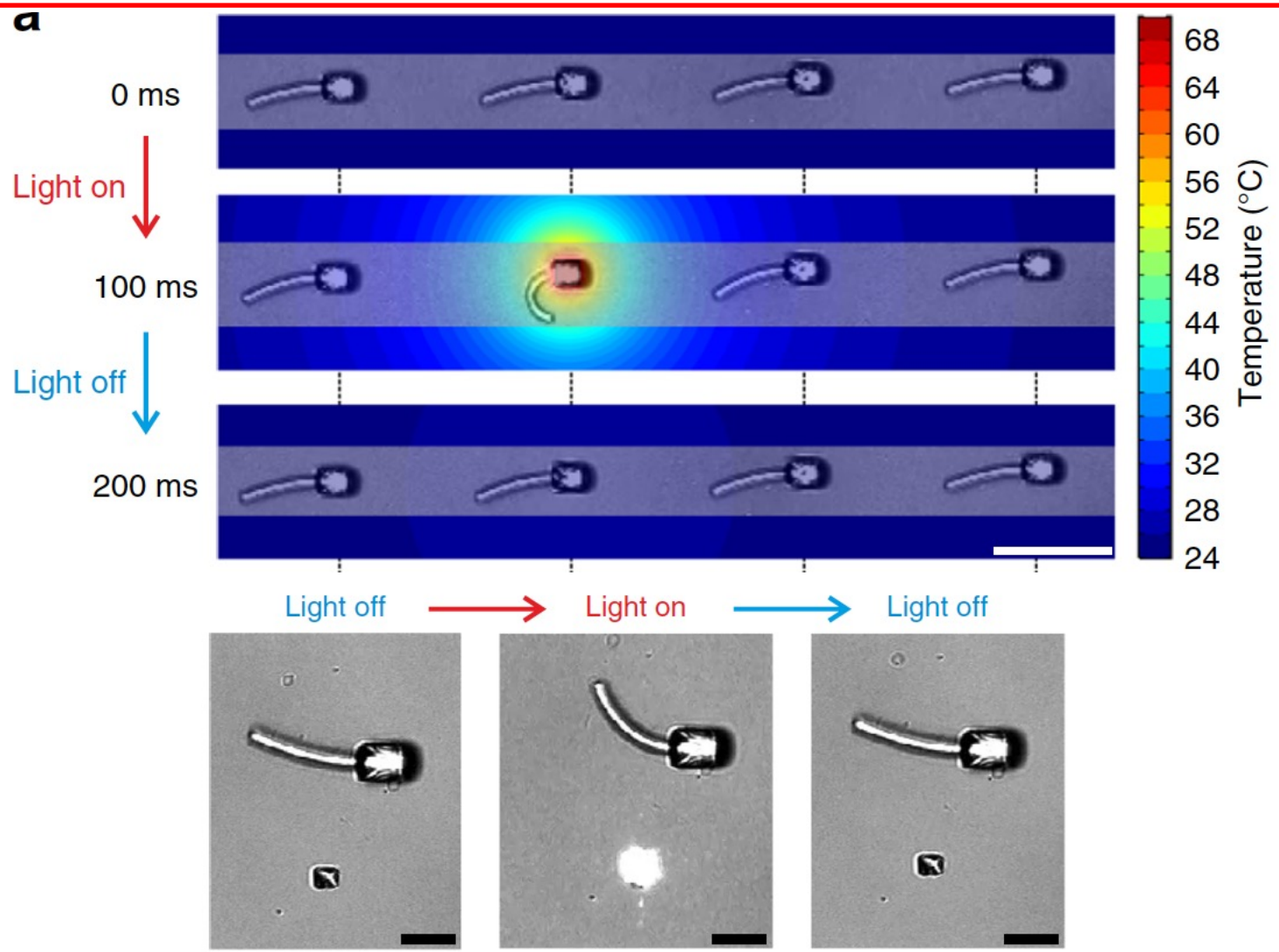






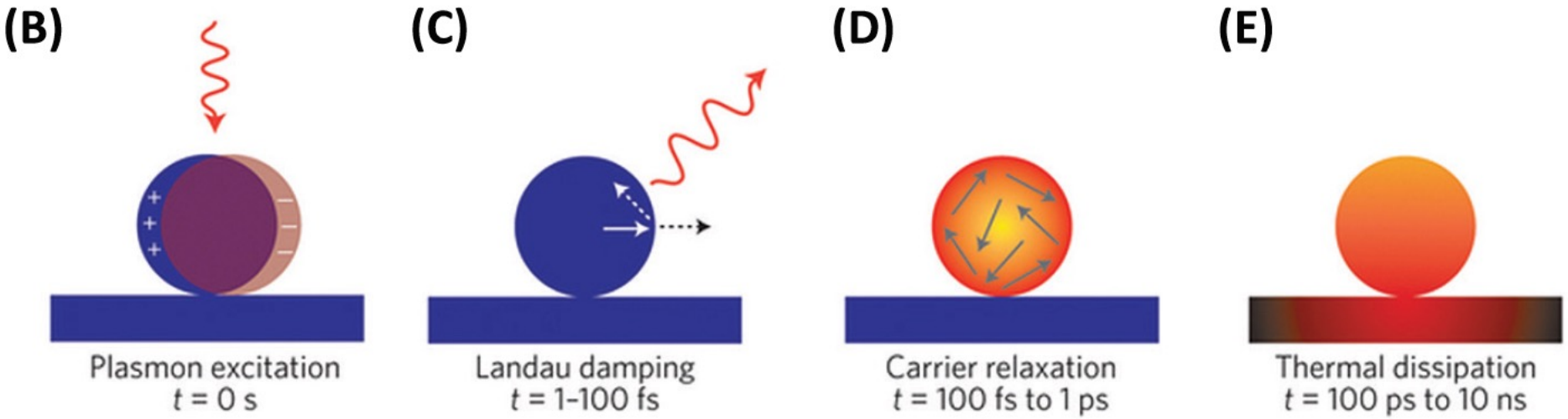


Laser-induced Actuation

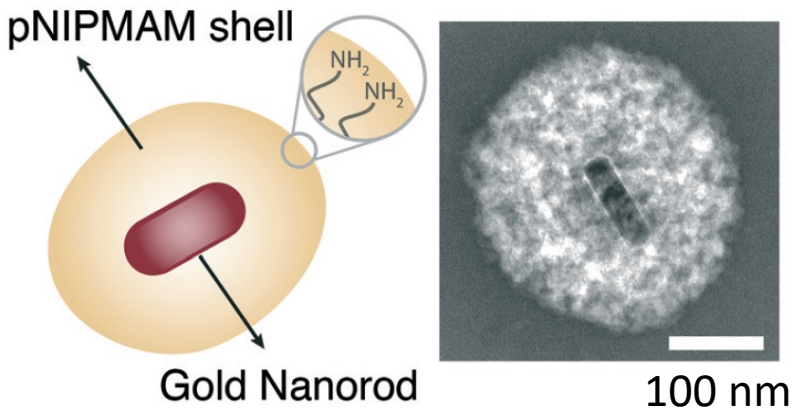


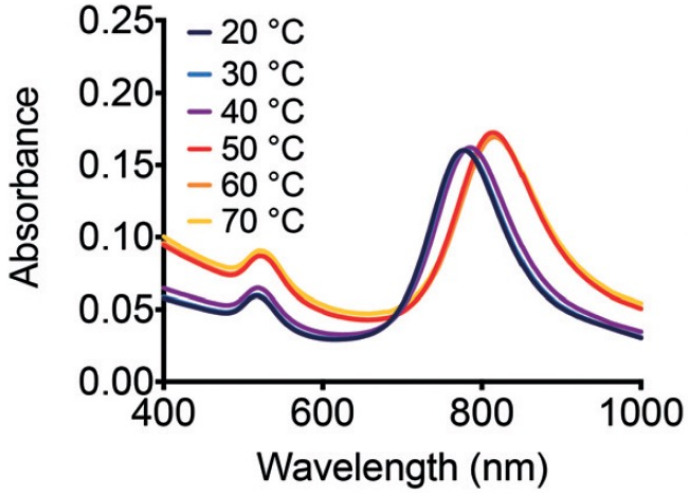
Plasmon Resonance

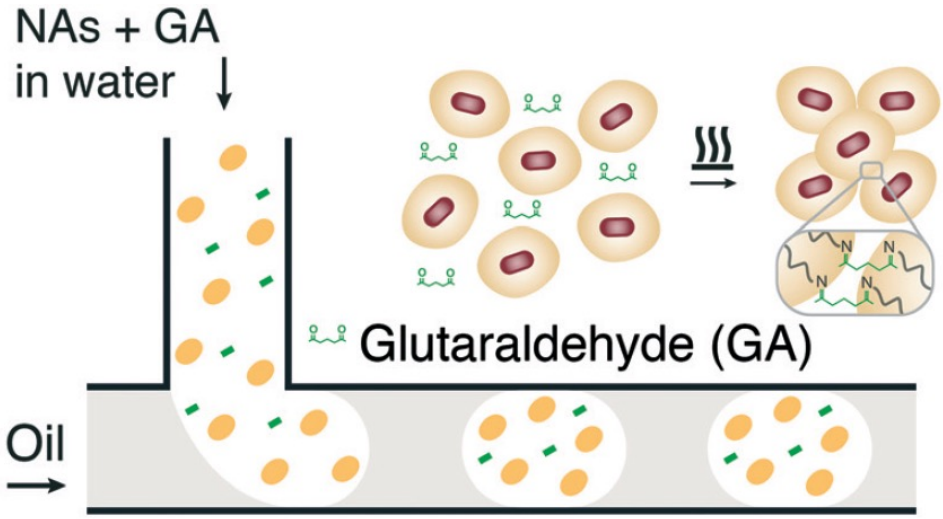
- The oscillating electromagnetic field of the light causes the free electrons of the gold nanoparticles to collectively coherently oscillate (about a metal-dielectric interface)
- Plasma like behavior of the electrons once they are labile
- Localized surface plasmon is geometrically confined to nanoparticle

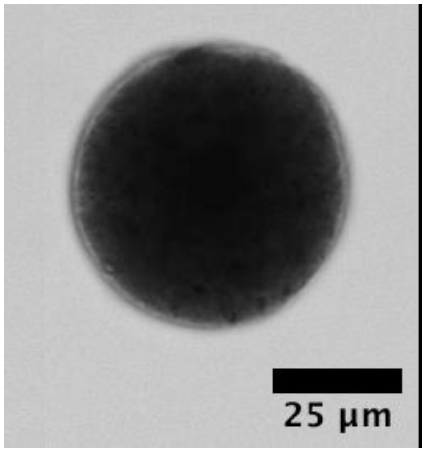


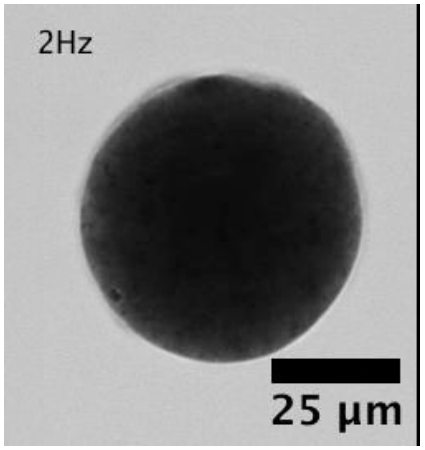
Optomechanical Nanoactuators



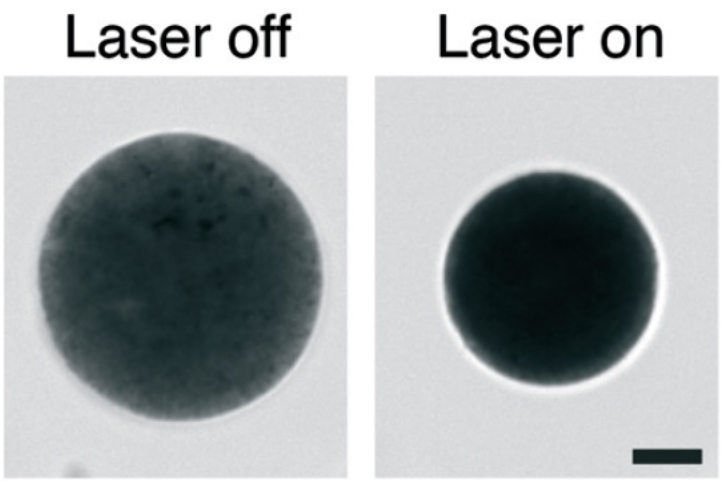


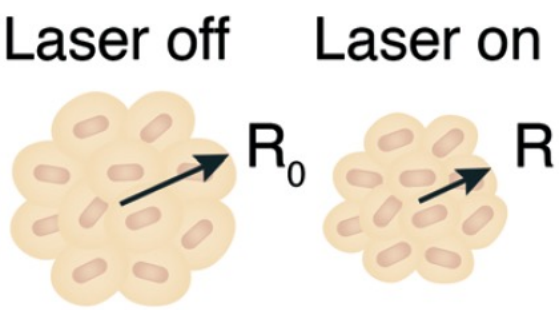






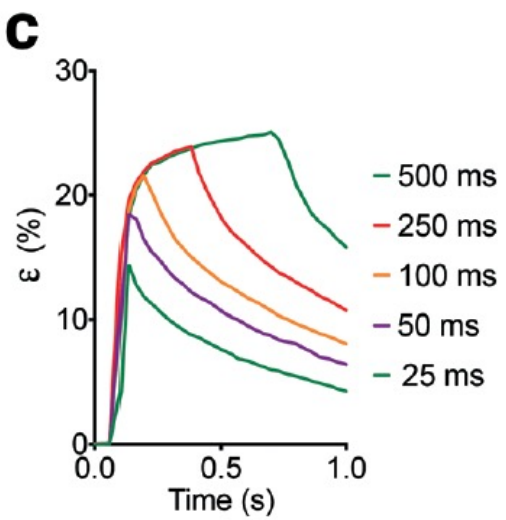
Plasmon Resonance

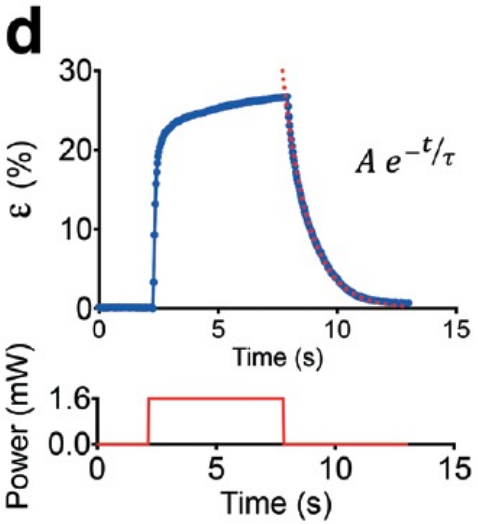


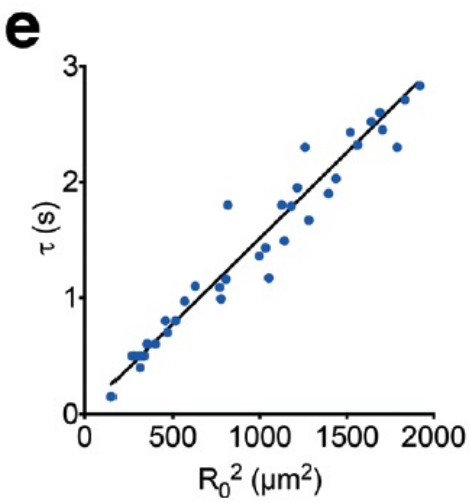


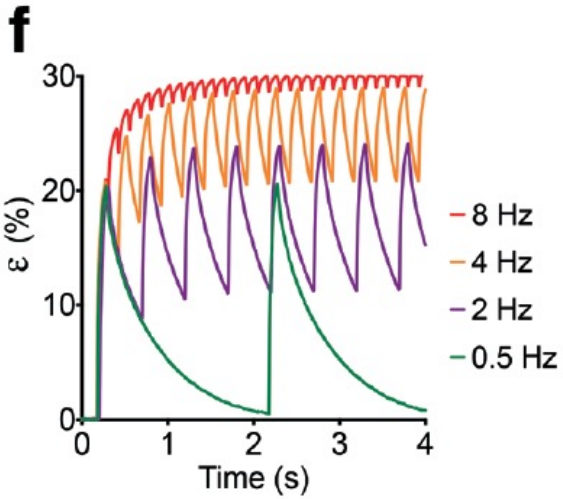
Actuation strain (%)

$$\varepsilon = \frac{R_0 - R}{R_0} \times 100$$

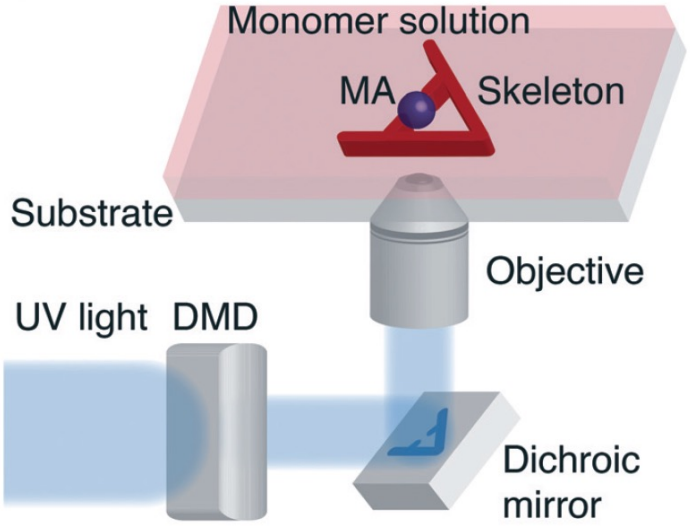


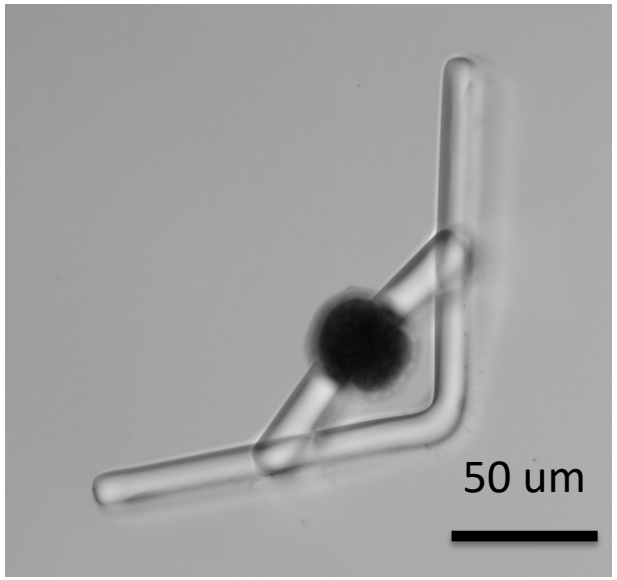


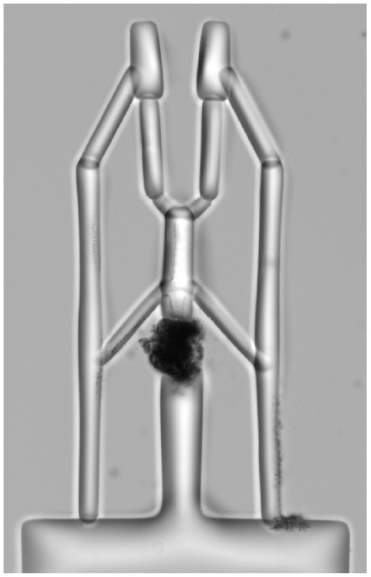


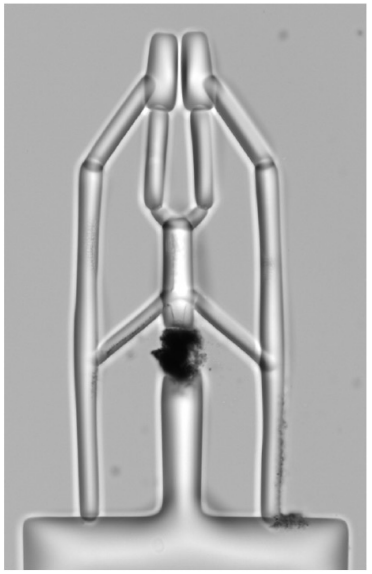


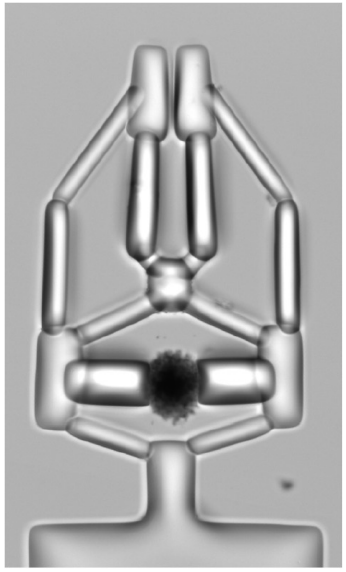
Hierarchical Assembly and Control

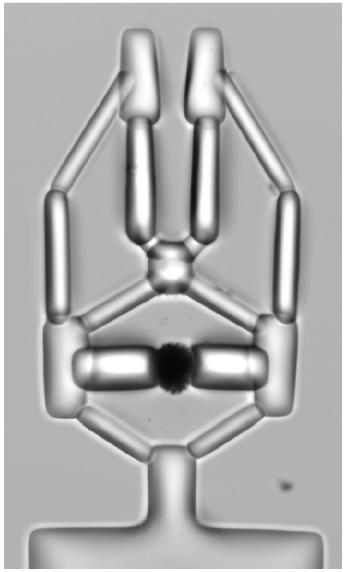




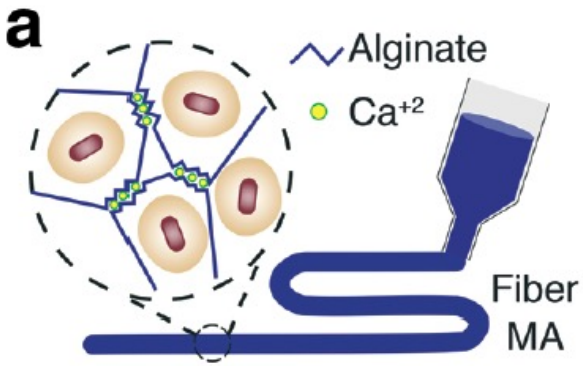


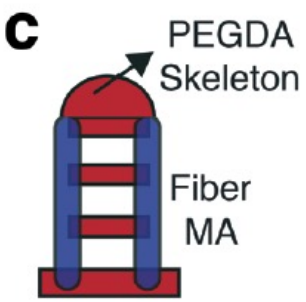


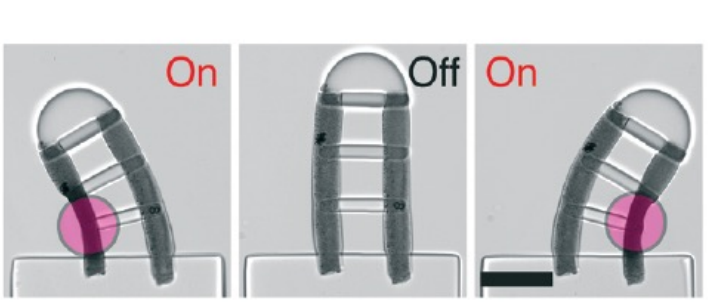


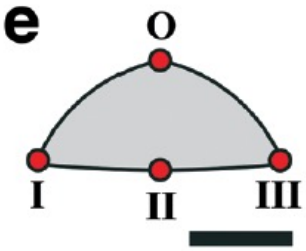


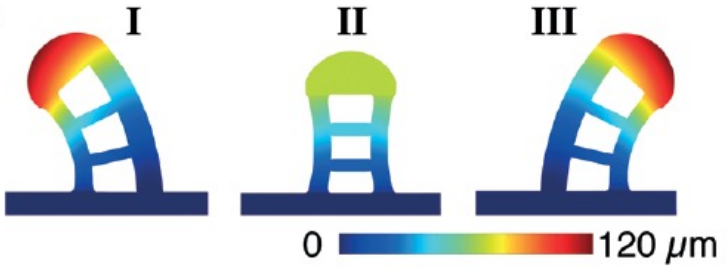
Hierarchical Assembly and Control

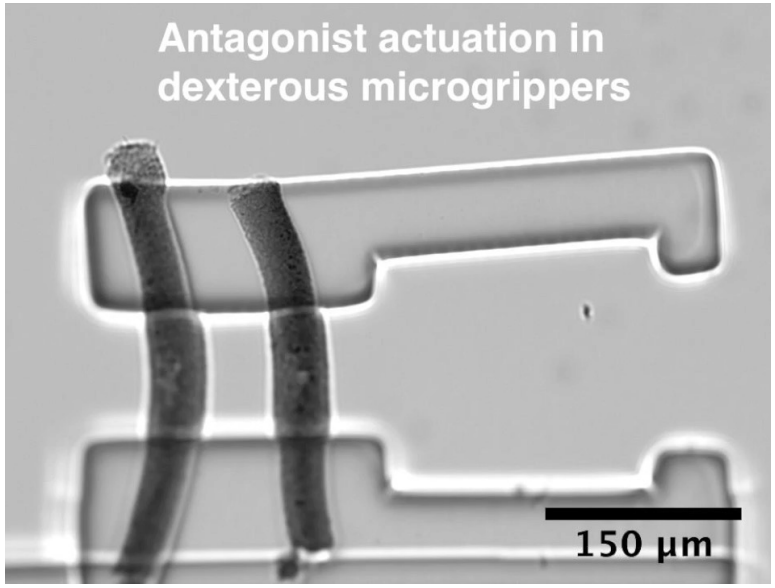


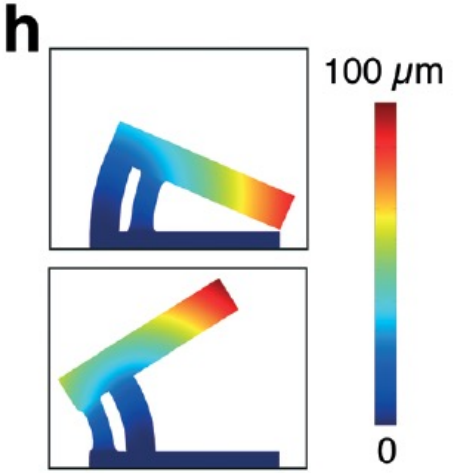






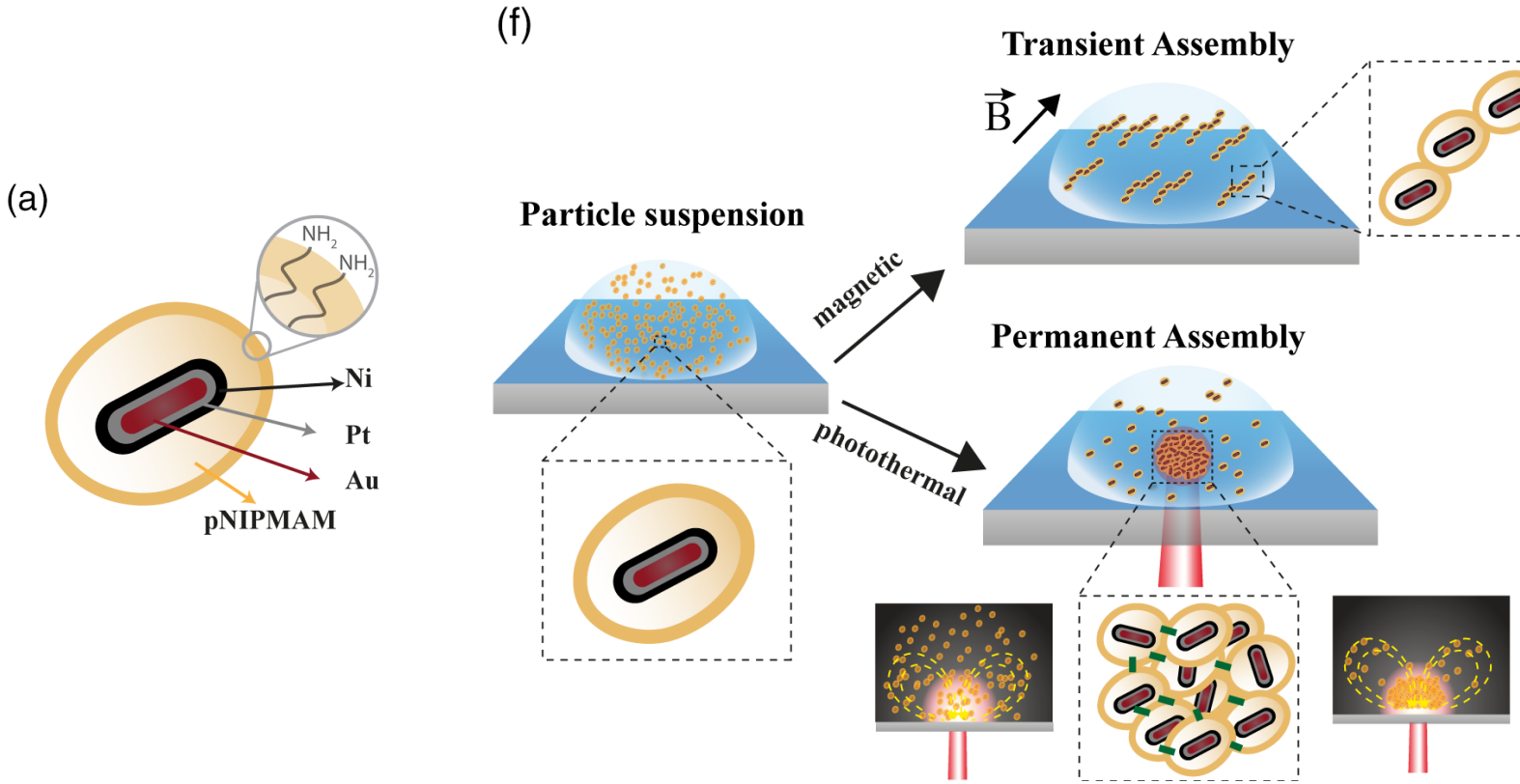




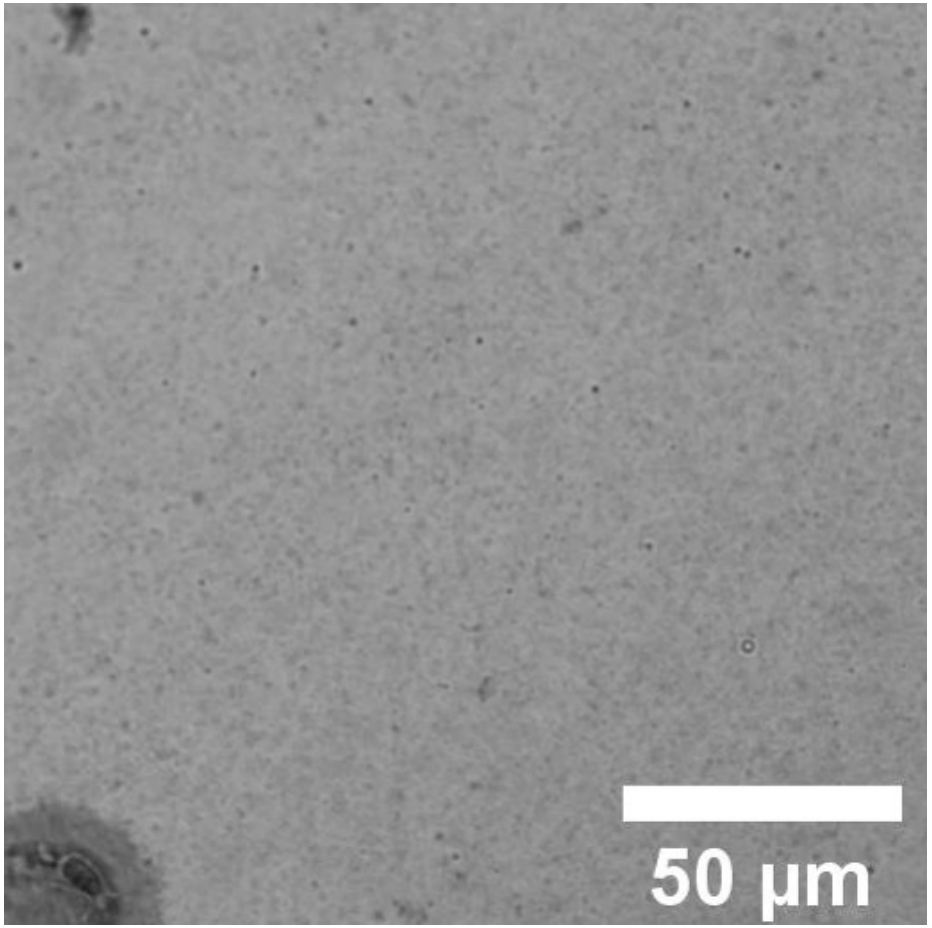


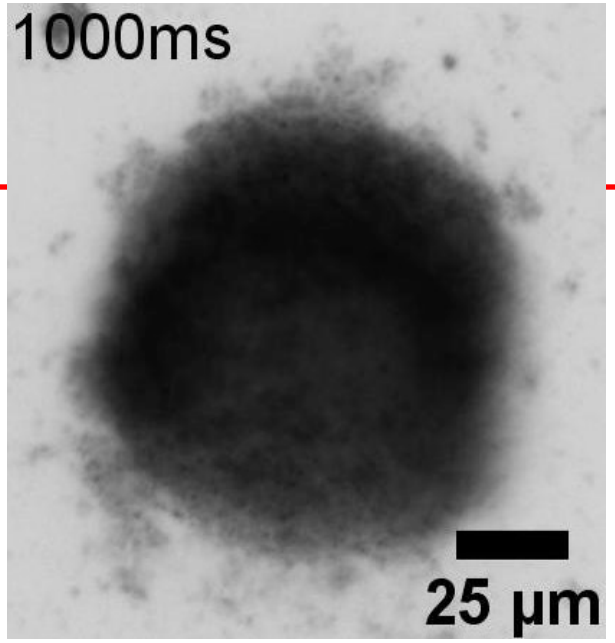
Colloidal assembly

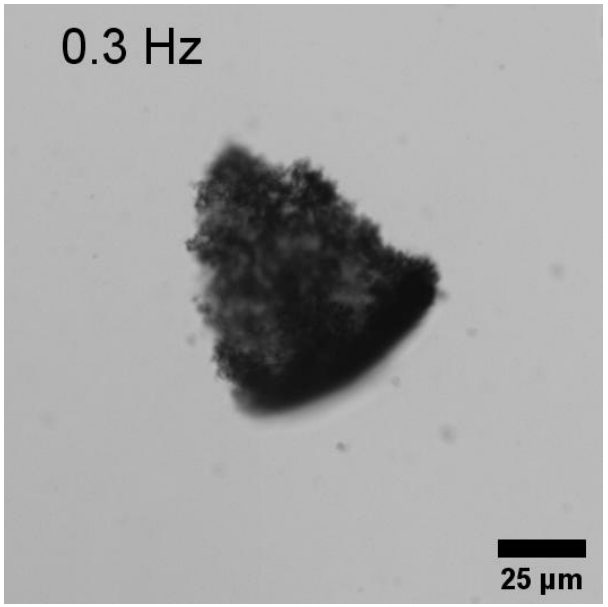
- Marangoni flows, photocatalytic reactions, magnetics



Colloidal assembly

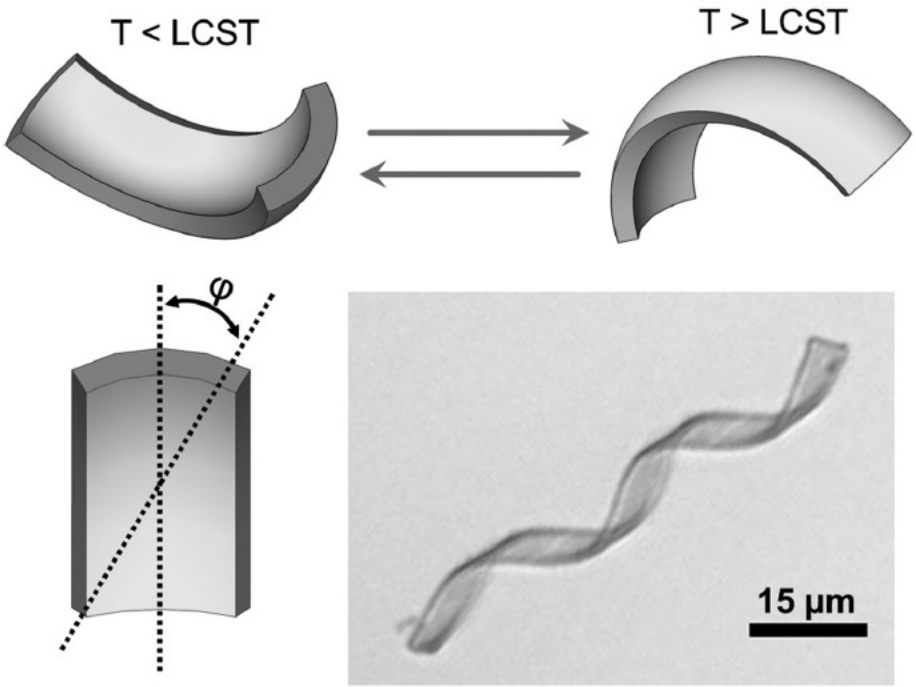


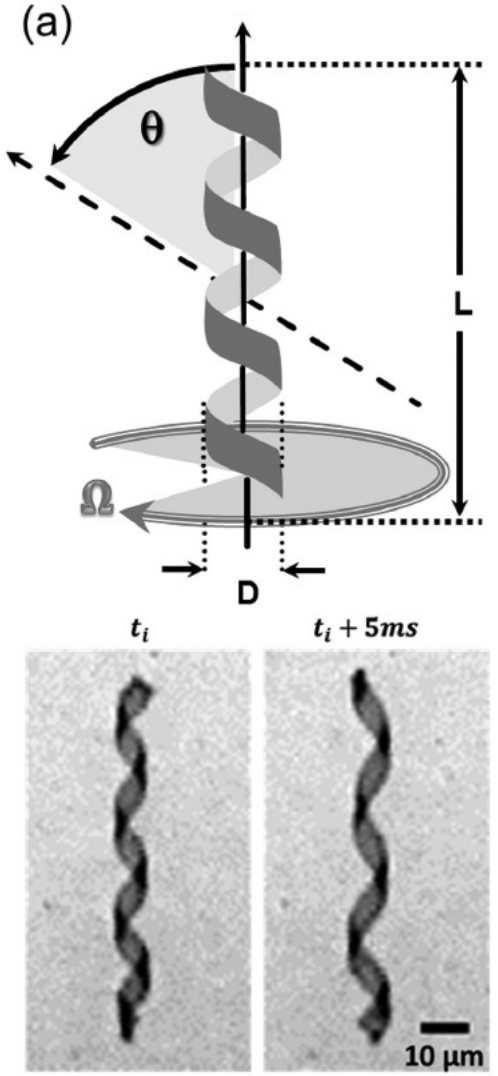




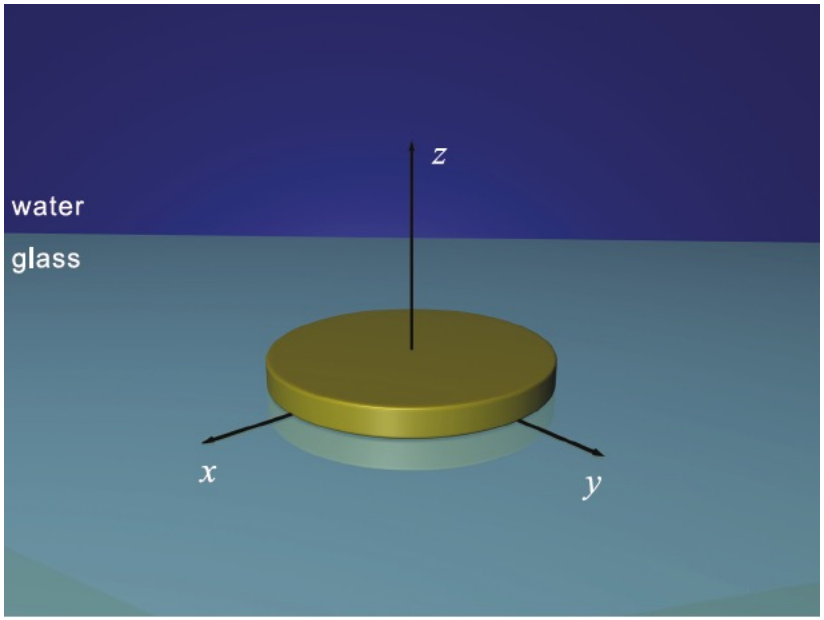
Photothermal mobile micromachines

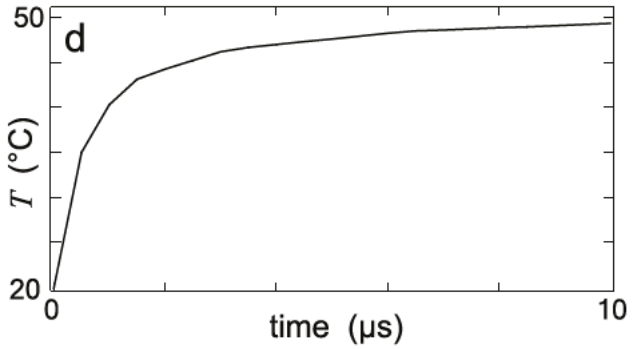
- From contraction of the gel to swimming

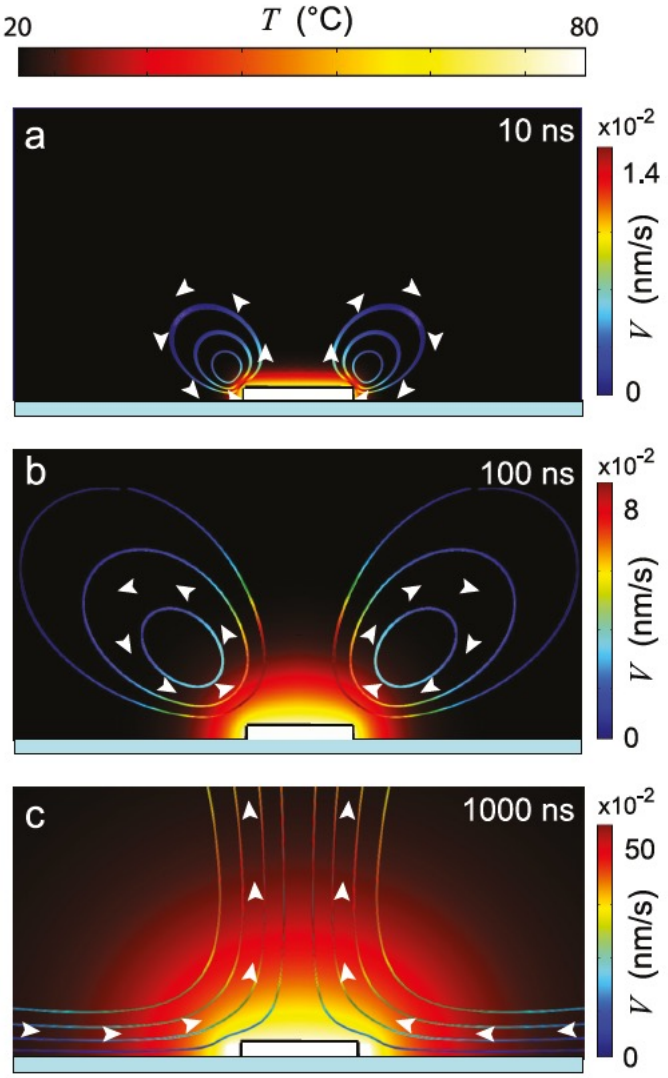




Plasmon Resonance: Fluid Convection

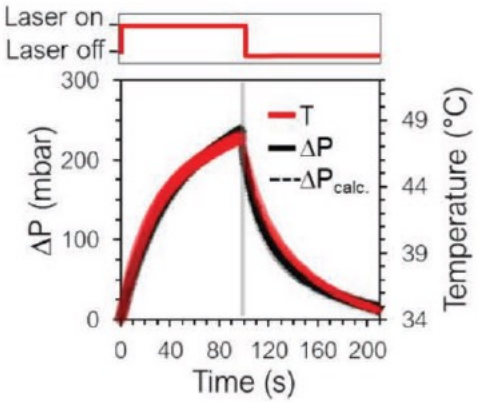


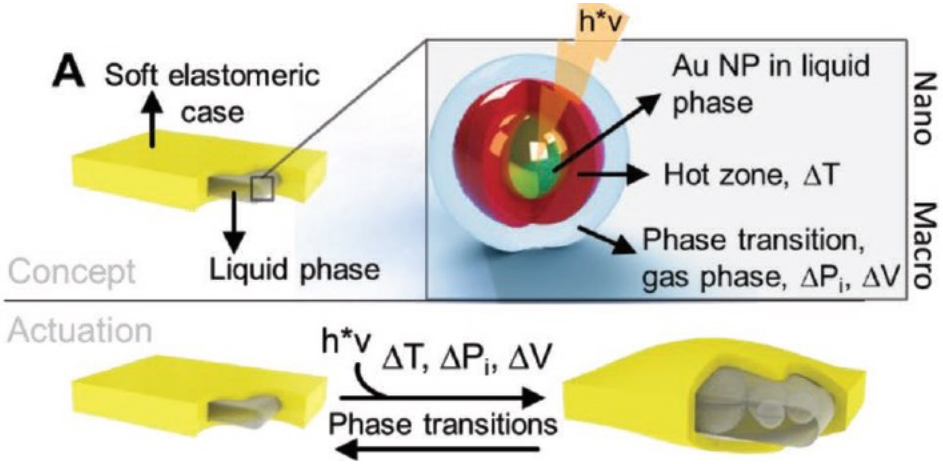




Photothermal steam engines

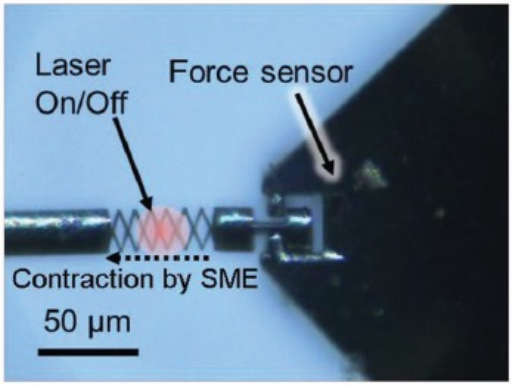
- Upon laser excitation, the nanoparticles convert light of specific wavelength into heat and initiate a liquid-to-gas phase transition.
- The related pressure increase inflates the elastomers in response to laser wavelength, intensity, direction, and on–off pulses.
- During laser-off periods, heating halts and condensation of the gas phase renders the actuation reversible.

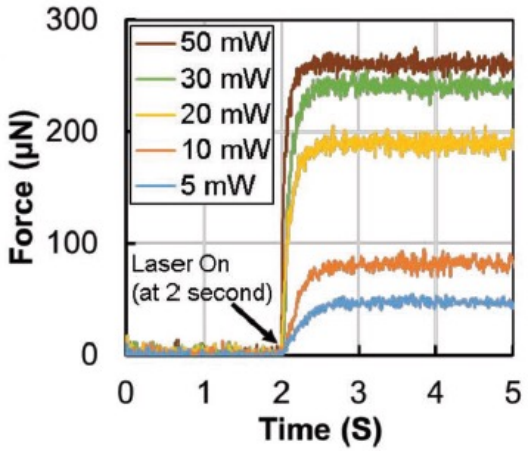




SMA Microactuators

- Heat induced phase transition

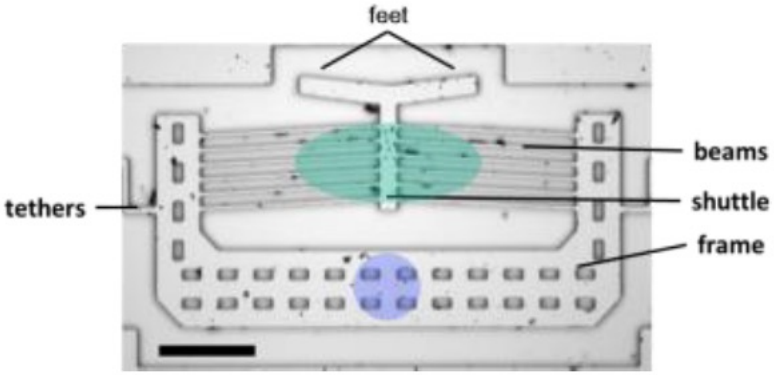




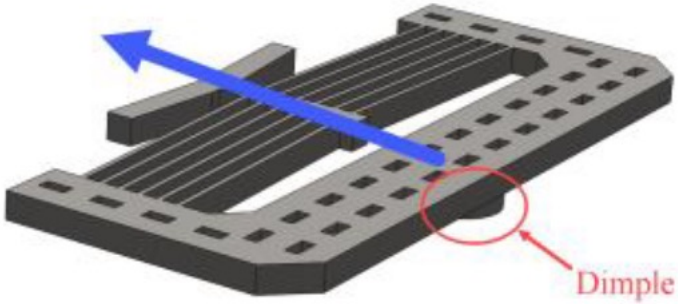
Specification	Muscle fiber	SMA microactuator [unit cell]
Maximum frequency [Hz]	500[2]	1600
Maximum actuation stress [MPa]	0.1–0.4[2]	0.75
Diameter [μm]	24.4 ± 1.1[29] (myofibril)	25
Length [μm]	1.6–2.5[30] (length of sarcomere)	8–25
Maximum deformation ratio	0.25–1.4[31,32]	0.15–0.6

Thermal expansion (impact drive)

- Based on expansion of materials due to temperature changes
- Temperature control: light absorption
- Direct expansion vs bending moment (bimorph actuator)
- Example: Actuated at resonance frequency: stick and slip motion



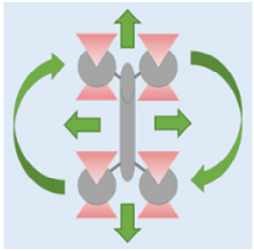
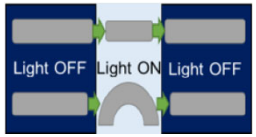
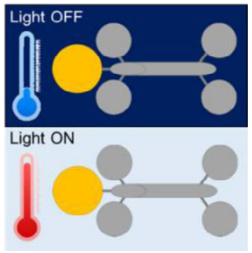
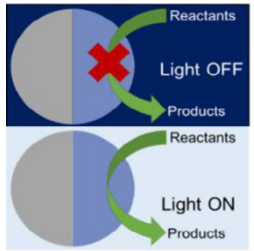
100 um



Constant	Quantity/Name	Value
R	Reflectivity of Silicon	0.3
T_{env}	Environment Temperature	20 ℃
ρ_{Si}	Silicon Density	$2328\ \mathrm{kg \cdot m^{-3}}$
h_{air}	Air convection constant	$10\ \mathrm{W \cdot (m^2 \cdot K)^{-1}}$
k_{air}	Air thermal conductivity	$0.025\ \mathrm{W \cdot (m \cdot K)^{-1}}$
c_{v-air}	Air specific heat	$716\ \mathrm{J \cdot (Kg \cdot K)^{-1}}$
k_{Si}	Silicon thermal conductivity	$124\ \mathrm{W \cdot (m \cdot K)^{-1}}$
$c_{v,Si}$	Silicon specific heat	$702\ \mathrm{J \cdot (kg \cdot K)^{-1}}$
α_{Si}	Silicon coefficient of thermal expansion	$2.6 \times 10^{-6}\ (℃)^{-1}$
θ	Theta (beam angle)	0.04991642 rad

Summary on mechanisms

Light as microrobot actuator

Core strategies for controlling the motion of polymeric microrobots		Further activation mechanisms enabled by light		
Optical trapping and manipulation of rigid microrobots, which often include spherical handles, can be done with six degrees of freedom. 	*Light-triggered shape changes* in soft stimuli–responsive microrobots can lead to various interesting microrobot motions and other operations when properly engineered. 	*Thermoplasmonic effects*—heat is generated by illuminating a gold-coated microrobot component due to plasmon resonances. 	*Photocatalytic effects*—chemical reactions occur only upon illumination, phenomenon often exploited on Janus particles. 	*Phototaxis behaviors* inspired from nature can be exploited for microrobot motion toward the light source, or away from it.