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Fiber Optic Tethered Microtools Built from Stiff/Soft Composites

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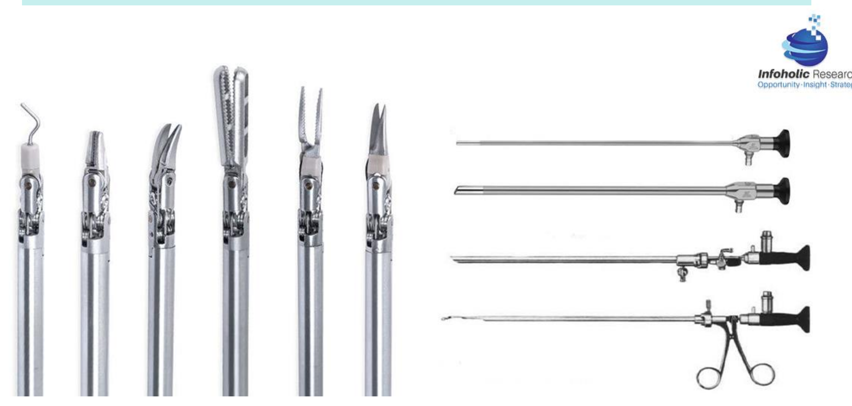
Problem

To enable precision biomedical procedures like microbiopsies and targeted drug delivery, minimally invasive surgical and diagnostic tools are becoming smaller and smarter, leading to improved health outcomes for patients. At the same time, biocompatible materials and compliant mechanisms are being developed in the field of soft robotics that allow for large deformations, varying stiffnesses, and environmental responsiveness. While these materials can be difficult to use to build complicated structures at very small scales, this is not the case for polymers used in multiphoton lithography (MPL), a nano/microscale additive manufacturing technique. In this work we aim to leverage soft robotics concepts and actuation mechanisms to build functional microtools using MPL.

Minimally invasive surgical instruments



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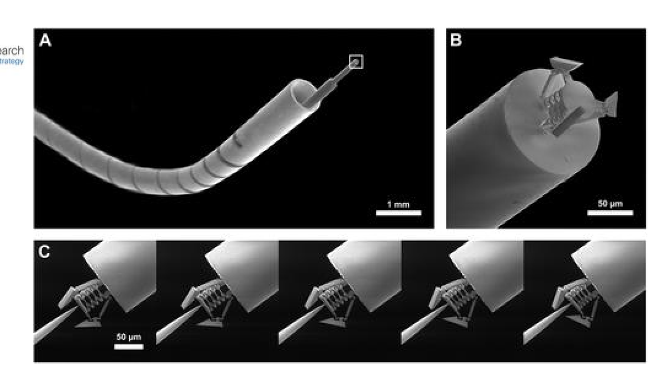
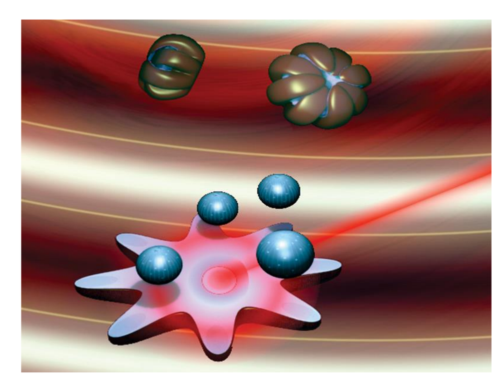
3D printed microgripper



Small. 2018 Apr;14(16):e1703964.

Soft microrobots



Adv. Mater., 26: 952-957

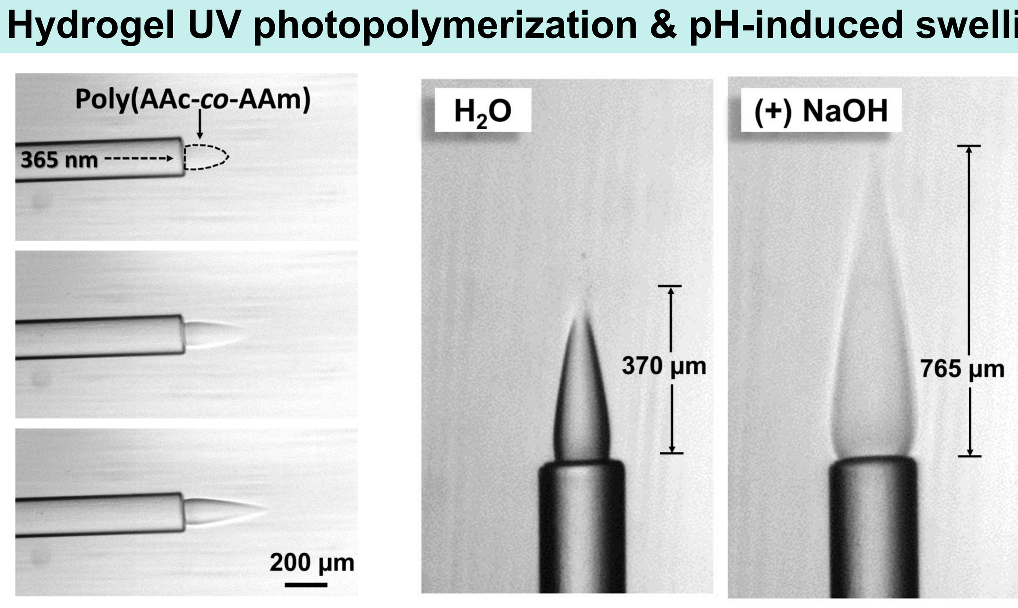
Overarching question: ***Can the macroscale concepts of soft robotics translate to the nano/microscale?***

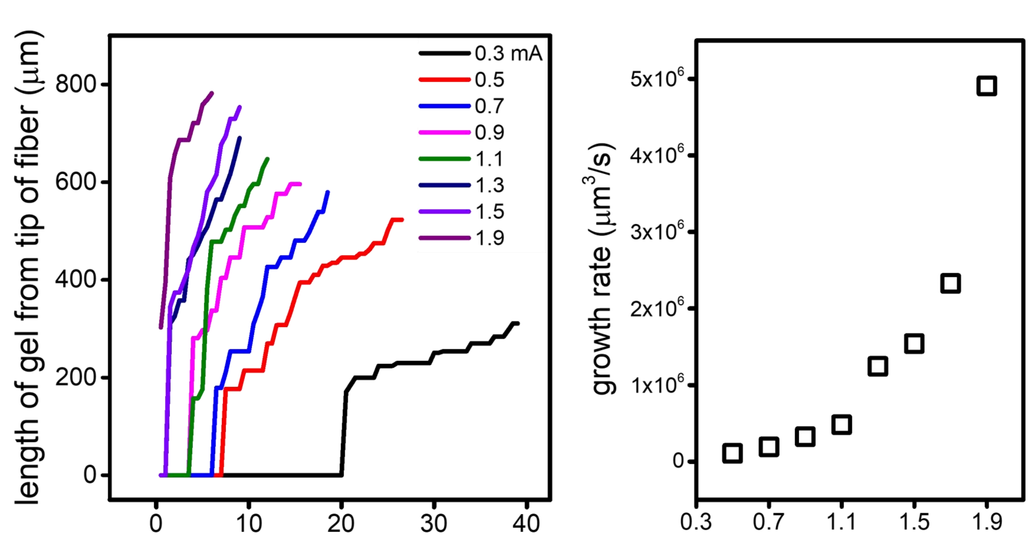
Approach

The microgripper *stiff/soft composite* structures were inspired by musculoskeletal actuators with a stiff but flexible resin "skeleton" and a soft hydrogel "muscle." Optical fibers were chosen as a modular build platform to guide the tethered microtools, enable hydrogel photopolymerization, and induce actuation.

We used two environmentally responsive hydrogels, pH responsive polyacrylamide-co-acrylic acid (poly(AAc-co-AAm)) and temperature responsive poly(N-isopropyl acrylamide) (PNIPAAM). These were photopolymerized on the fiber tip using ultraviolet (365 nm) light output from the fiber. The gel growth response to varying the driving LED brightness was characterized to allow for controlled fabrication.

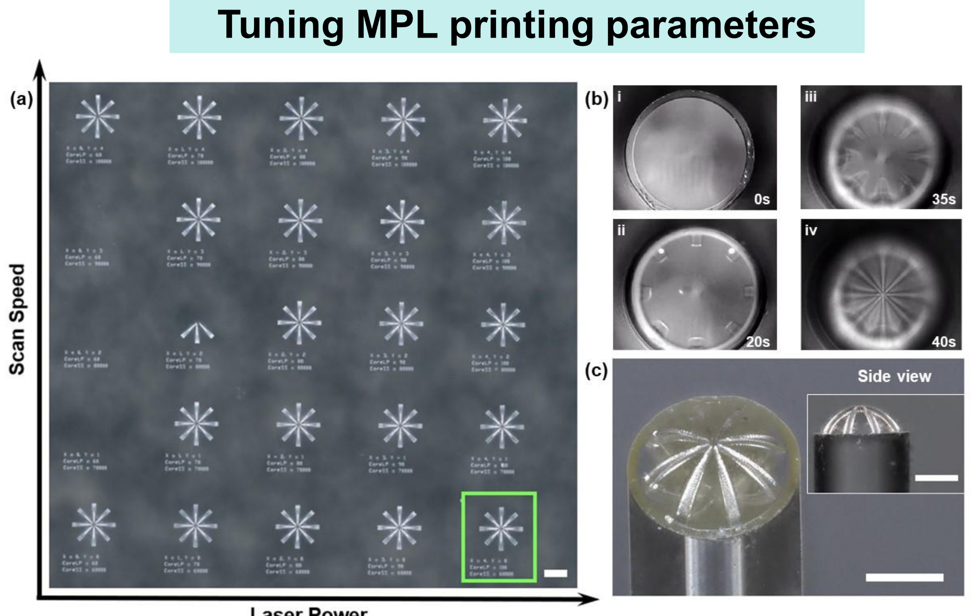
Hydrogel UV photopolymerization & pH-induced swelling



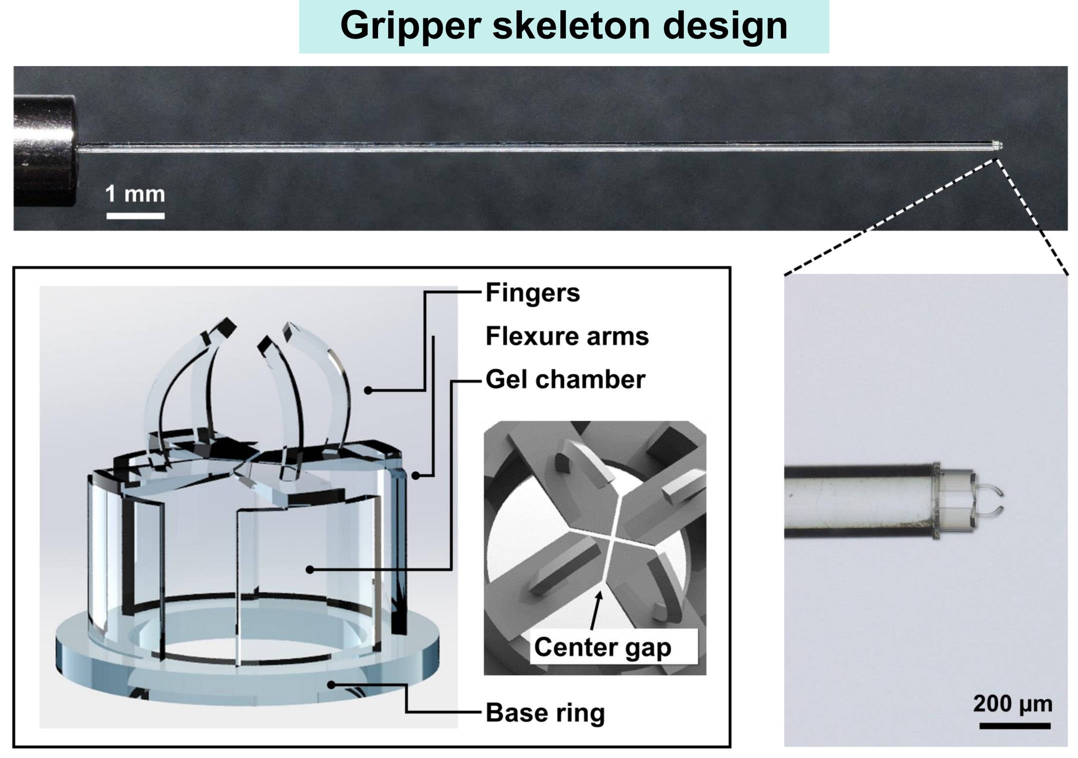


The skeletons were fabricated out of IP-S resin on a Nanoscribe printer with a custom fiber holder insert. The grippers were designed with a base ring to attach to the fiber tip and a windowed gel chamber to contain the polymerized hydrogel and facilitate rinsing. The grippers are actuated when the hydrogel swells/de-swells in response to changing environmental conditions and pushes/pulls on the flexure arm(s) to open/close the gripper fingers. Besides the microgrippers shown here, we explored additional tool geometries for gripping and cutting.

Tuning MPL printing parameters

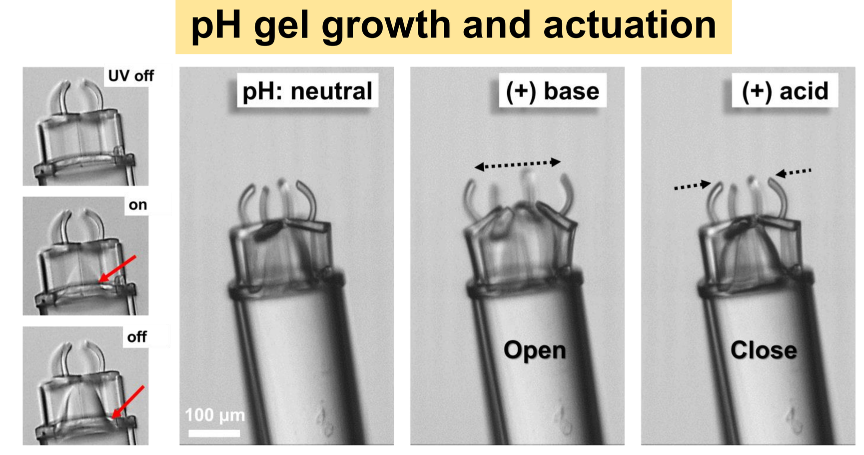


Gripper skeleton design

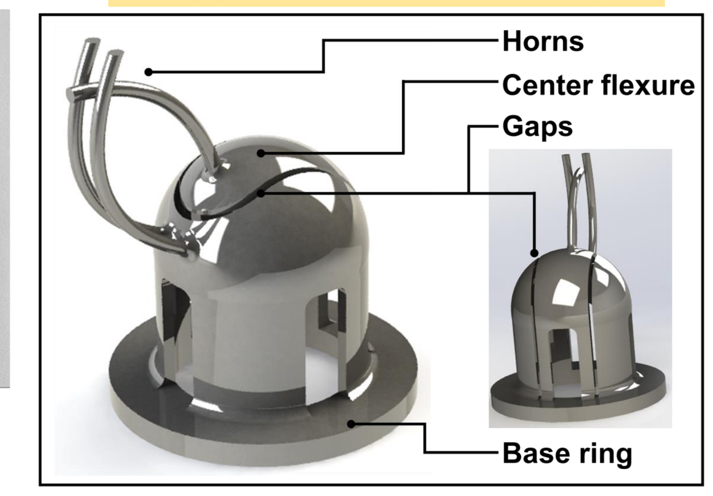


Results

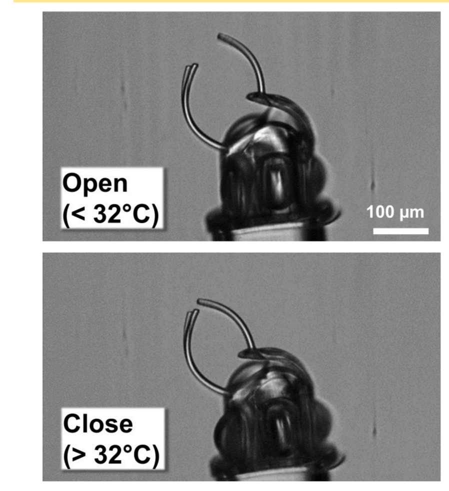
pH gel growth and actuation



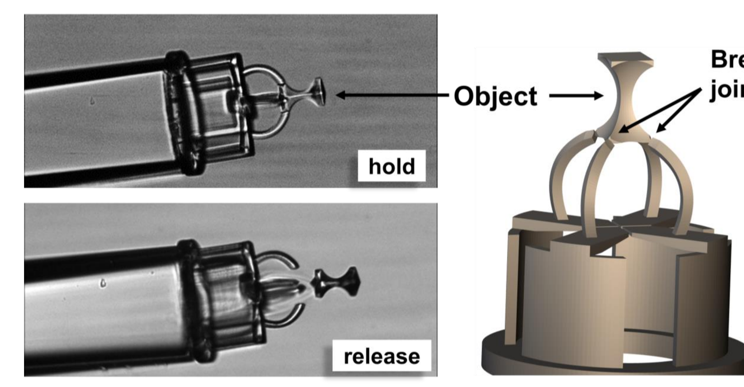
Gripper v2 skeleton design



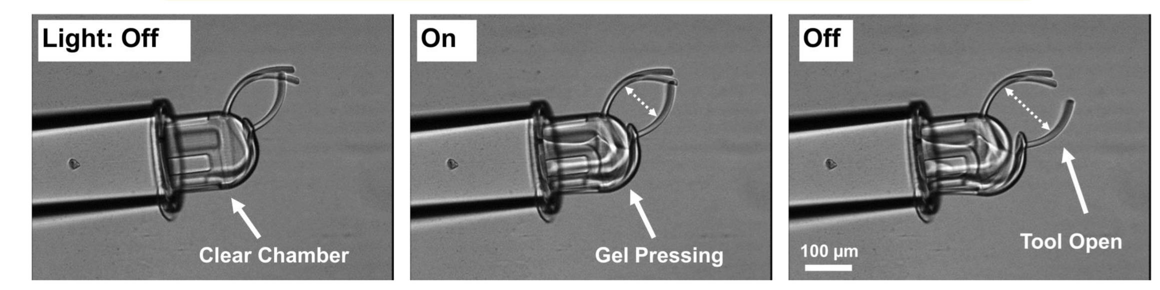
Temperature actuation



Object manipulation

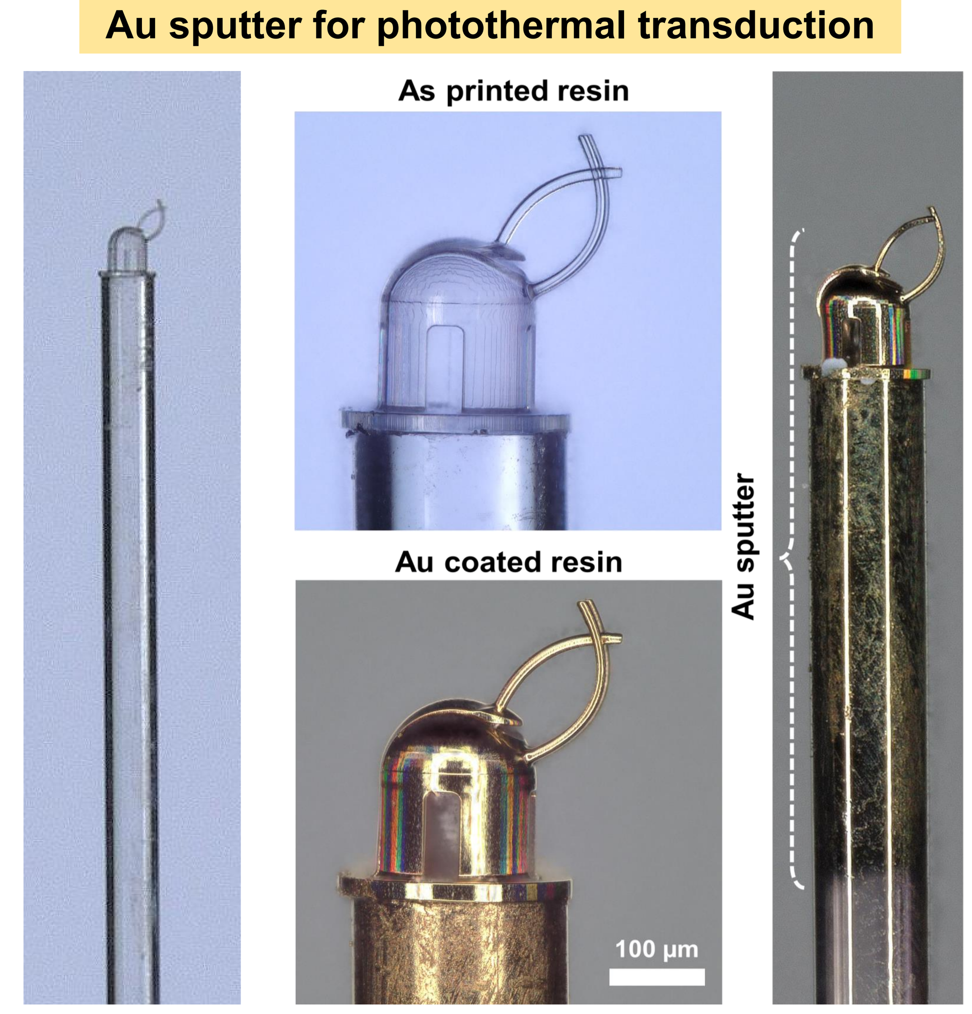


UV light mediated temperature gel growth

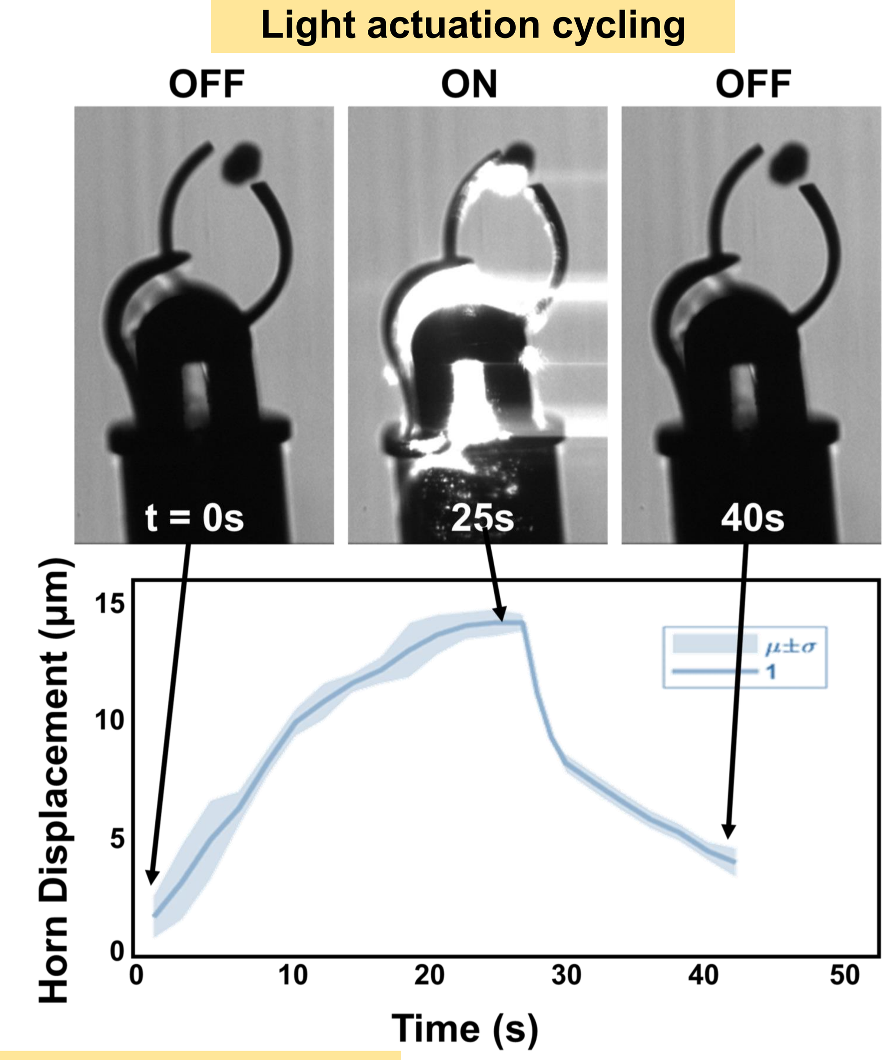


We successfully actuated both pH responsive and temperature responsive fiber tethered microgrippers and demonstrated the microgrippers' ability to grasp and release small objects. The most successful method to achieve gripper actuation via white light output from the fiber optic was sputter coating the printed skeleton with 70nm gold before growing temperature-responsive PNIPAAM hydrogel on the fiber tip. These gold coated grippers were easier to test for repeatability and durability than the other types, lasting for over 500 actuation cycles without any signs of wear. The opening of the gripper arms is shown to be controllable through the timing and duration of light pulses.

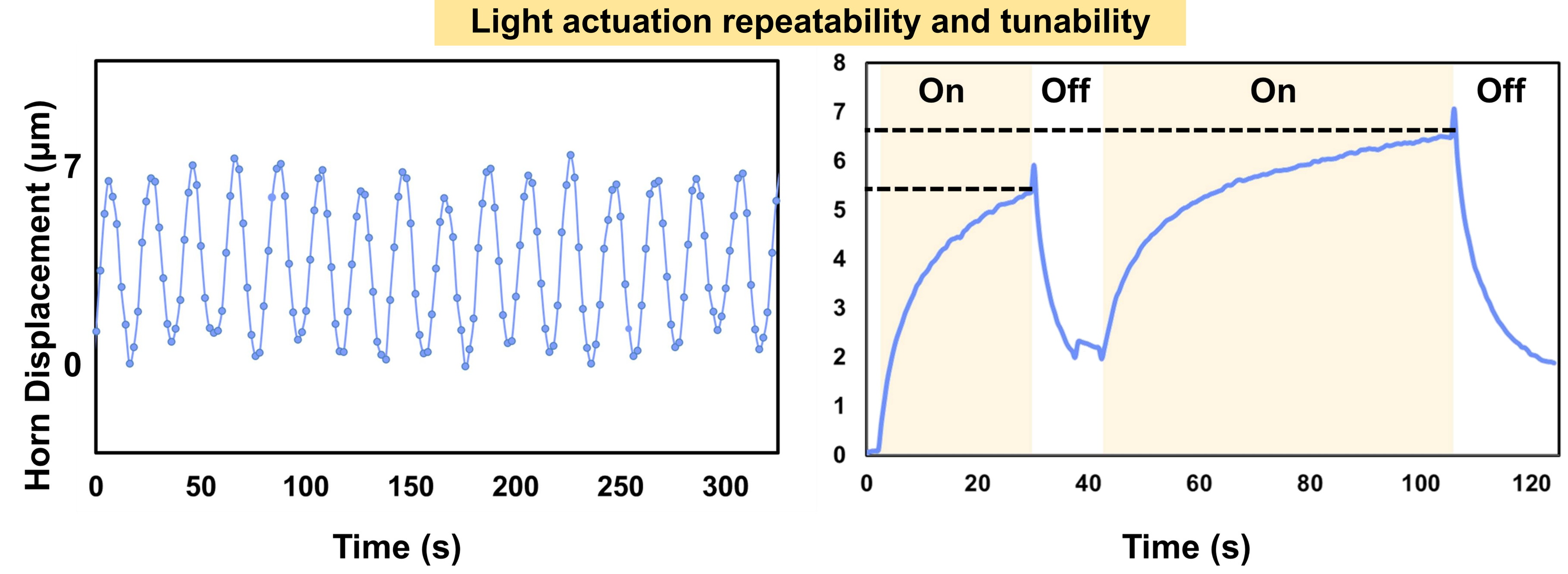
Au sputter for photothermal transduction



Light actuation cycling



Light actuation repeatability and tunability



Significance

We have demonstrated how materials that actuate in response to pH, temperature, and light can be used in functional microscale devices. With this new modular design, a variety of tools can be constructed for autonomous or controlled gripping, cutting, and manipulating of structures on the cellular level. Incorporation of additional functionality (e.g., electrical/magnetic properties) can further expand the design space and applicability of stiff/soft composite microtools introduced in this work.

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