3D MICROPRINTING OF MULTI-ACTUATOR SOFT ROBOTS ONTO 3D-PRINTED MICROFLUIDIC DEVICES *VIA EX SITU* DIRECT LASER WRITING

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ABSTRACT

Soft robots have emerged as powerful alternatives to their rigid counterparts due to inherent advantages including safety for human-robot interactions and adaptability for manipulating delicate objects. Despite recent developments for macroscale multi-actuator soft robots, manufacturing challenges have impeded the miniaturization of such systems due to difficulties in facilitating the macro-to-micro fluidic connections required for controlling soft robots with fluidic actuation schemes. To bypass these barriers, here we introduce a novel "*ex situ* Direct Laser Writing (*es*DLW)"-based hybrid strategy for additively manufacturing mesoscale 3D multi-actuator soft robotic systems directly atop externally accessible microfluidic devices. Specifically, we use two-photon *es*DLW to 3D microprint sophisticated mesoscale multi-actuator soft robotic systems directly on top of—and notably, fluidically sealed to—externally accessible "Digital Light Processing (DLP)"-based 3D-printed microfluidic devices. We interrogated the efficacy of this strategy by loading fluorescently labeled fluids into the *es*DLW-printed soft actuators as well as by performing cyclic burst-pressure experiments. Experimental results revealed uncompromised print-to-microdevice fluidic integrity both qualitatively from an absence of undesired leakage of the fluorescently labeled fluid and quantitatively for 100 cycles of pressure ramping up to 500 kPa inputs. In combination, these results suggest that the presented *es*DLW strategy holds promise as a pathway for scaling fluidically actuated soft robotic systems down to the mesoscale for emerging applications, such as for robot-assisted surgical interventions.

KEYWORDS

Soft Robots, Additive Manufacturing, 3D Printing, Direct Laser Writing, Digital Light Processing

INTRODUCTION

Often taking inspiration from nature, soft robots can be designed to mimic biological systems in the way they move and complete tasks [1,2]. Soft robots are made of compliant materials and have garnered increasing attention due a number of benefits over traditional rigid-bodied robots, particularly in terms of safety for human-robot interactions as well as adaptability for manipulating geometrically complex and/or delicate objects [3,4]. These characteristics make soft robots uniquely well suited for uses in biomedical applications, such as for robot-assisted surgical interventions and as drug delivery vehicles [5,6].

Additive manufacturing (or colloquially, "three-dimensional (3D) printing") has emerged as a robust candidate for soft robot fabrication by providing a pathway to complex, yet advantageous system designs and autonomous, repeatable robot construction [7]. Despite recent developments for macroscale multi-actuator soft robots by our group [8] and others [9-11], manufacturing hurdles have impeded the miniaturization of such systems. One particular challenge for fluidically actuated soft robots is the ability to achieve the macro-to-micro fluidic interfaces that are needed to deliver pneumatic and/or hydraulic inputs into the miniaturized robotic systems [12-14]. Thus, alternative manufacturing strategies that address this issue are in critical demand to enable new classes of mesoscale fluidically actuated soft robotic systems.

Among current additive manufacturing technologies, "Two-Photon Direct Laser Writing (DLW)" offers unparalleled geometric versatility and control with resolutions on the order of 100 nm [15]. Researchers have demonstrated how using DLW to print 3D micro-structures onto macroscale objects can benefit applications in the fields of optics and photonics [16,17] as well as microrobotics [18]. Recently, our group demonstrated such "*ex situ* DLW (*es*DLW)"

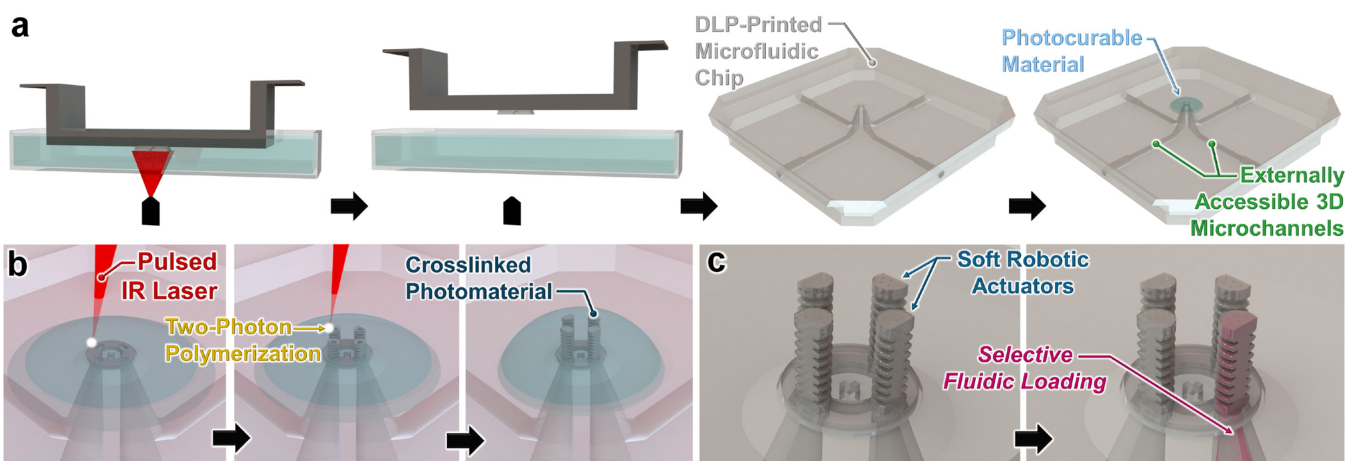

***Figure 1:** Conceptual illustrations of the presented strategy for "ex situ Direct Laser Writing (esDLW)"-based 3D microprinting of meso-scale multi-actuator soft robotic systems atop externally accessible "Digital Light Processing (DLP)" 3D-printed microfluidic chips. **(a)** DLP 3D printing (left) of a microfluidic chip with externally accessible microchannels. Photomaterial is dispensed atop the microchannel ports (right) prior to loading in the DLW 3D printer. **(b)** The esDLW strategy for 3D microprinting multiple soft actuators directly atop (and fluidically sealed to) the DLP-printed microfluidic chip. **(c)** After development (to remove uncured photomaterial), input pressures can be applied independently to target actuators and fluids can be infused into and through the actuators for burst-pressure characterizations.*

strategies for printing 3D microfluidic technologies atop fluidic tubing [19,20]. Here we explore the potential for extending our *es*DLW approach to overcome the aforementioned challenges to miniaturization by enabling mesoscale multi-actuator soft robotic systems to be 3D microprinted directly onto—and notably, fluidically sealed to—externally accessible microfluidic devices.

CONCEPT

In this work, we introduce a hybrid additive manufacturing strategy for printing mesoscale multi-actuator soft robotic systems onto microfluidic devices (**Fig. 1**). Our approach comprises three primary steps. First, DLP-based 3D printing—a vat photopolymerization approach in which a photocurable material is selectively crosslinked in a layer-by-layer manner—is used to fabricate a microfluidic chip with externally accessible microfluidic channels (**Fig. 1a**). After developing the print to remove any residual DLP-associated photomaterial, a droplet of DLW-compatible photomaterial is dispensed atop the output ports of the microchannels (**Fig. 1a** – *right*). The device is then loaded into a DLW 3D printer, and the multi-actuator soft robot is *es*DLW-printed directly onto the microfluidic chip by scanning a femtosecond pulsed IR laser in a point-by-point, layer-by-layer manner to selectively crosslink the photomaterial in target locations *via* two-photon (or multi-photon) polymerization phenomena (**Fig. 1b**). Importantly, each actuator is printed to align to a distinct, corresponding microchannel output port of the DLP-printed chip. After development, fluids can be loaded *via* the distinct channels of the microfluidic device into desired actuators of the *es*DLW-printed soft robotic system (**Fig. 1c**).

MATERIALS AND METHODS

Digital Light Processing (DLP)-Based 3D Printing of the Microfluidic Chip

The microfluidic device was designed with externally accessible microchannels to allow for facile and targeted fluidic loading into the DLW-printed soft actuators. The microfluidic chips were designed using the computer-aided design (CAD) software, SolidWorks (Dassault Systèmes, France), and printed using the MiiCraft M50 3-D (CADworks3D, Ontario, Canada) DLP printer with the CADworks3D Clear Microfluidics Resin. After the print was completed, the devices were rinsed with isopropyl alcohol (IPA) to remove uncured photoresin from the surface of the device. The devices were then soaked in methanol for 1 min to facilitate clearing of the resin from the interior channels before using pressurized N_2 gas to clean the remaining resin from inside the channels. After removing the residual resin, the devices were UV cured for 10 s and, following a 30 s waiting period, flipped and UV cured for an additional 10 s. The devices were then rinsed with methanol and UV cured for a final 10 s period before being placed in vacuum for 24 hours to remove any residual organic solvents from the chip.

Ex situ Direct Laser Writing (*es*DLW)-Based 3D Microprinting of Multi-Actuator Soft Robotic Systems

The multi-actuator soft robotic systems were designed using the SolidWorks CAD software, exported as an STL file, and then imported into the computer-aided manufacturing (CAM) software, Describe (Nanoscribe GmbH, Karlsruhe, Germany), to generate the DLW laser writing path. The photoresist, IP-Q (Nanoscribe), was dispensed atop the DLP-printed microfluidic chip fully covering the output ports. The device was then loaded into the Nanoscribe Photonic Professional GT2 DLW system in the Dip-in Laser Lithography (DiLL) mode configuration with the 10× objective lens. The multi-actuator soft robotic systems were printed directly atop the DLP-printed microfluidic chips fully aligned to the output ports of the device. To ensure a complete fluidic seal between the microfluidic chip and the soft robotic system, the interface of the top surface of the microfluidic chip was found manually, and the printing process was initiated with approximately 50 μm of overlap between the base of the soft robotic system and the top of the microfluidic chip. Upon completion of the *es*DLW process, the multi-actuator soft robot was developed in propylene glycol methyl ether acetate (PGMEA) for 60 min and rinsed with IPA to remove any uncured photoresist. A vacuum pressure was then applied to each microchannel to remove any remaining uncured photoresist from the actuators. The devices were then dried with N_2 gas.

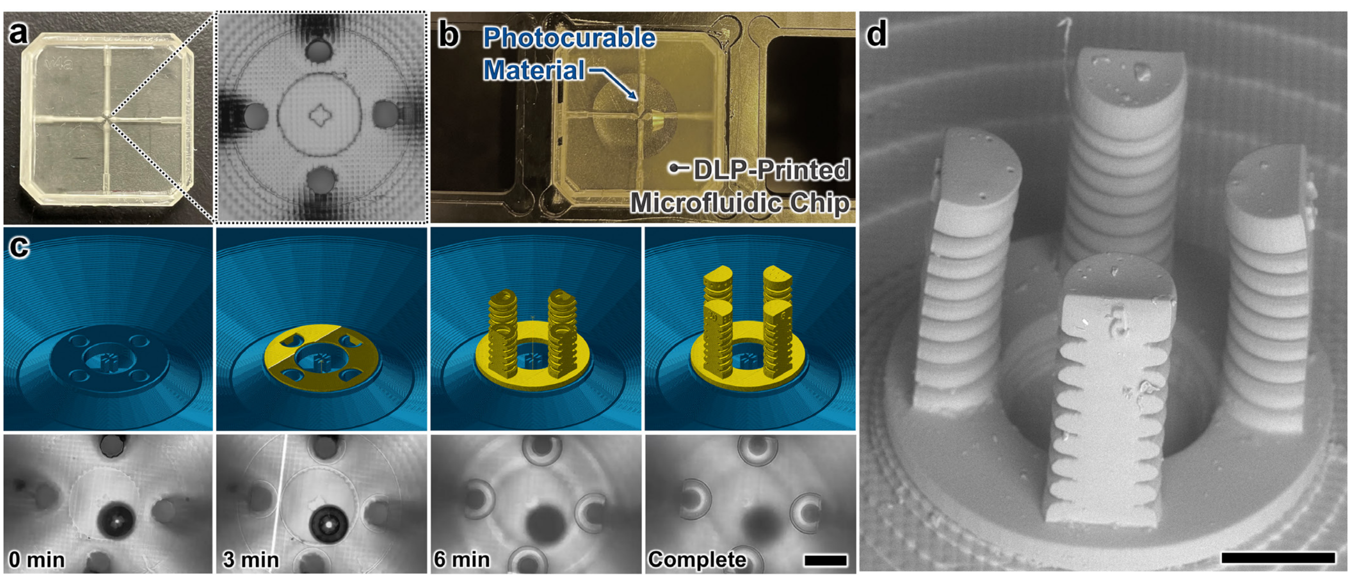

Figure 2: Fabrication results. ***(a,b)*** *The DLP-printed microfluidic device* ***(a)*** *before and* ***(b)*** *after dispensing the photomaterial atop the output ports.* ***(c)*** *Computer-aided manufacturing (CAM) simulations (top) and corresponding micrographs of the esDLW process (bottom) for 3D microprinting a multi-actuator soft robotic system directly onto the externally accessible microfluidic device (with each actuator aligned to a distinct, corresponding output port).* ***(d)*** *SEM micrograph of print results. Scale bars = 250 µm.*

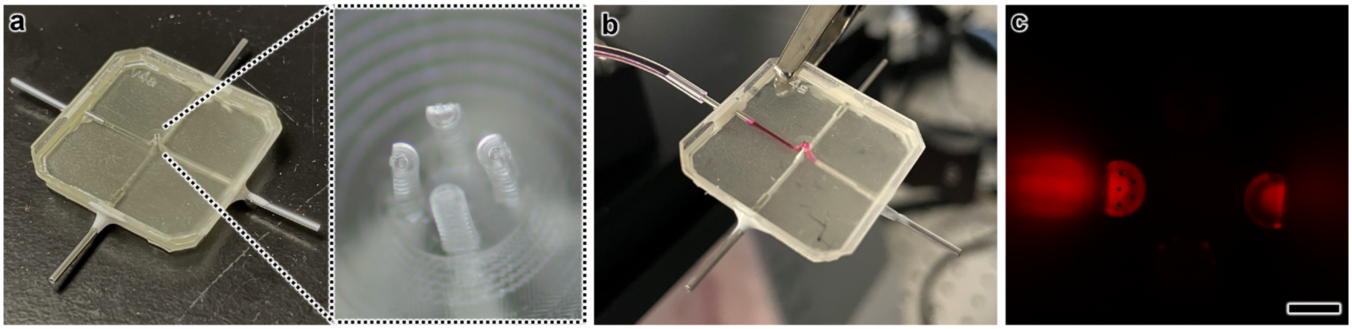

*Figure 3: Fluidic loading experimental results. **(a)** Images of the multi-actuator soft robotic system on the microfluidic chip prior to fluidic infusion. **(b)** Fluorescently dyed fluid infused through a channel and up (and out) a soft actuator. **(c)** Fluorescence micrograph of fluid in the soft actuator. Scale bar = 250 µm.*

Optical Characterization

Scanning electron microscope (SEM) images of fabrication results were obtained using a TM4000 Tabletop SEM (Hitachi, Tokyo, Japan). Brightfield and fluorescence imaging were performed using an inverted fluorescence microscope (Axio Observer.Z1, Zeiss, Germany) connected to a charge-coupled device (CCD) camera (Axiocam 503 Mono, Zeiss). Angled brightfield images were obtained using the Monocular Max 300x microscope objective connected to the Hayer 41MP HD 1080P camera (ShenZhen Hayear Electronics Co. Ltd, China).

Fluidic Experimentation

Fluidic testing was performed using the Fluigent Microfluidic Control System MFCS and OxyGEN software (Fluigent, France). The multi-actuator soft robotic systems were loaded with DI water using fluorinate ethylene propylene fluidic tubing (Cole-Parmer, Vernon Hills, IL) and stainless-steel catheter couplers (20 ga., Instech, Plymouth Meeting, PA). Three separate cyclic burst-pressure experiments were performed corresponding to applied input pressures of approximately 100 kPa, 250 kPa, and 500 kPa for 1.5 s, but then set to 0 kPa for 1.5 s after each pressure increase for all cases. Each set of experiments were performed for n = 100 cycles. For fluorescence imaging, the multi-actuator soft robot was loaded with fluorescently labeled DI water (Rhodamine B, MilliporeSigma, St. Louis, MO) at pressures of 1–3 kPa.

RESULTS AND DISCUSSION

esDLW-Based Fabrication

As a preliminary investigation of the efficacy of using *es*DLW to print soft actuators, we fabricated a multi-actuator soft robotic system directly atop DLP-printed microfluidic chips. The chips comprised four externally accessible microchannels with top outlet ports (diameter ≈ 140 μm) and side input ports with diameters of approximately 900 μm to fit 20 ga. stainless steel couplers (**Fig. 2a**). We designed the overall dimensions of the DLP-printed microfluidic device to allow for facile loading into the Nanoscribe DLW 3D printer (**Fig. 2b**). CAM simulations and corresponding micrographs of the *es*DLW process for printing the multi-actuator soft robot directly onto the microfluidic chip are presented in **Figure 2c**. The entire *es*DLW process was completed in less than 8 min. Use of the 10× objective lens during the *es*DLW process allowed the entire multi-actuator soft robot to be printed as a unified system in a single print run (*i.e.*, without any stitching). SEM micrographs of the completed multi-actuator soft robots revealed effective alignment and integration of the multiple soft robotic actuators with each designated fluidic outlet port (**Fig. 2d**). The SEM micrographs also showed no defects or breaks along the interface between the DLP-printed microfluidic chip and the multi-actuator soft robot.

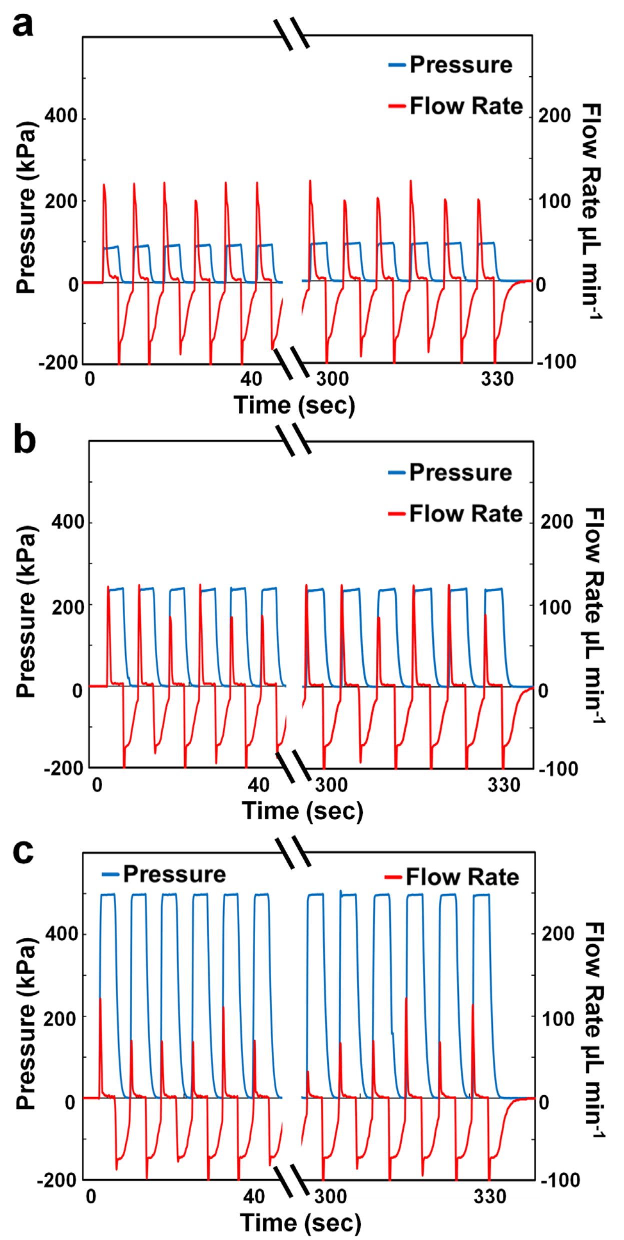

*Figure 4: Experimental results for cyclic burst-pressure testing for n = 100 cycles (per distinct pressure) with fluorescent DI water corresponding to cycles 1–6 and 94–100 for input pressures of: **(a)** 100 kPa; **(b)** 250 kPa; and **(c)** 500 kPa.*

Fluidic Experimentation

As an initial measure of manufacturing efficacy, we performed fluidic loading experiments in which a fluorescently labelled fluid was inputted into the individual actuators to ensure there were no fluid leaks in the microfluidic chip (**Fig. 3a,b**). Fluorescence images of fluidic loading revealed that fluid was restricted to the interior microchannels and the soft actuators (**Fig. 3c**). These results also provided initial evidence supporting effective fluidic sealing between the DLP-printed microfluidic chip and the *es*DLW-printed multi-actuator soft robot system. To more thoroughly interrogate the integrity of this fluidic interface, we performed cyclic burst-pressure experiments for input pressures of 100 kPa, 250 kPa, and 500 kPa (n = 100 cycles for each case). Experimental results for the inputted pressures and corresponding flow rates did not reveal phenomena associated with undesired burst events or fluidic leakage (**Fig. 4**). Specifically, the flow rates consistently returned to 0 μL/min before the input pressure returned to 0 kPa for each pressure cycle for all cycles of all three pressures tested, including for 500 kPa—the upper limit of our experimental setup. Furthermore, we did not observe any significant changes in the flow rate peaks over the course of the experimental runs (**Fig. 4**). In combination, these results suggest that the presented hybrid 3D printing strategy yielded robust fluidic sealing between the DLP-printed microfluidic chip and the *es*DLW-printed soft robotic system, thereby satisfying a key capability for applications that demand high levels of pressurization associated with target soft robotic functionalities.

CONCLUSIONS

In this work, we explored the viability of using *es*DLW to print mesoscale multi-actuator soft robotic systems directly atop DLP-printed externally accessible microfluidic devices. The *es*DLW fabrication and experimental results revealed uncompromised fluidic sealing between the *es*DLW-printed soft actuators and the DLP-printed chip up to 500 kPa for n = 100 cycles. Future efforts should focus on investigating actuation routines for such soft robotic systems as a function of inputted pressures. Although the current study centers on fluidically actuated soft robots, it should be noted that the manufacturing strategy could be extended to a diversity of fields, including for the development of organ-on-a-chip systems. Nonetheless, the mechanical integrity and fluidic loading results demonstrated here can provide a foundation for future soft robotic applications, such as for robot-assisted surgical interventions.

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