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DIGITAL MANUFACTURING OF MICROFLUIDIC SYSTEMS USING ULTRALOW-COST LCD PHOTOPOLYMERIZATION 3D PRINTERS FOR WIDESPREAD ADOPTION

Houda Shafique, Vahid Karamzadeh, Yonatan Morocz, Andy Ng, and David Juncker
McGill University, Montreal, QC, Canada

Digital manufacturing (DM) strives for automated and seamless manufacturing from digital file to functional product. DM of ready-to-use microfluidic systems in <1 h is now possible thanks to high resolution 3D printing by digital light processing (DLP), capillaric circuits (CCs) that operate free-of-peripherals via structurally-encoded liquid handling algorithms [1-2], and hydrophilic inks that circumvent the need of post-processing steps [3]. However, adoption of DM is predicated on DLP printers that cost ~15K-30K USD, which limits widespread implementation as the capital cost constitutes too high an entry-barrier for many potential users. In addition, DLP printers with ~3M pixels face a trade-off between footprint and resolution, which limits device size and manufacturing throughput. Here, we introduce DM of microfluidics using ultralow-cost liquid crystal display (LCD) photopolymerization 3D printers that retail for ~300 USD with ~8M pixels. (Figure 1). We introduce an ink optimized for making high resolution microchannels on these "hobbyist" LCD printers and illustrate versatility by making embedded 3D micromixers and CC-based diagnostic chips.

Although both LCD and DLP printers work by photopolymerizing an ink layer-by-layer using UV light, LCD suffers from a lower light intensity (LCD: 2-5 mW/cm^2, DLP: 20-30 mW/cm^2), thus presenting a need for low viscosity, fast curing inks. Furthermore, common photoadsorbers have an absorbance peak ~385 nm while LCD printers only operate at 405 nm, which further slows curing time. To address these constraints, we introduced a photoink based on polyethylene(glycol)diacrylate-250 supplemented with pentaerythritol tetra-acrylate with additional acrylate groups and diphenyl(2,4,6-trimethylbenzoyl) phosphine oxide as photoinitiator with an activation peak between 380-425 nm, which reduced polymerization time to 1.3 s on the LCD printers. Embedded microchannels as small as ~126 x 250 μm^2 (width x height) were made and integrated into CCs for autonomous sequential delivery (Figure 2).

To illustrate the potential of LCD printers, we first 3D printed a microfluidic mixer with intersecting and overlapping conduits [4] with ~146 μm feature width and characterized mixing under laminar flow (Figure 3). Next, we made a CC with a microfluidic chain reaction [1] in its application towards an enzyme-linked immunosorbent assay (ELISA)-on-a-chip [2] for the detection of interferon-γ, which is a widely used biomarker for tuberculosis diagnosis. Requiring <20 μL sample volume, the ELISA-chip produced a colorimetric readout in 45-min with an excellent limit of detection in buffer (12 pg/mL, CV: 6.8%), and with the capability to process biofluids such as plasma and whole blood (Figure 4). Finally, thanks to the large build-plate of the LCD printer, a 5-plex ELISA-chip was printed at once in 45-min, corresponding to a manufacturing throughput of 53 ELISA-chips/8h/printer (Figure 5). The 5-plex chip reduces the pipetting steps from 25 to 9, as reagents are supplied via common inlet and automatically distributed and metered, and only unique samples are delivered individually; upon initiation, all 5 assays are executed and timed automatically.

The various demonstrations of microfluidics and CCs made on ultralow-cost "hobbyist" LCD printers using readily available ink formulations pave the way for the widespread adoption of microfluidics made ready-to-use by distributed DM.

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Figure 1: Process flow of ultralow-cost 3D printing on photopolymerization LCD printers that retail ~300 USD for high resolution and throughput DM of CCs.

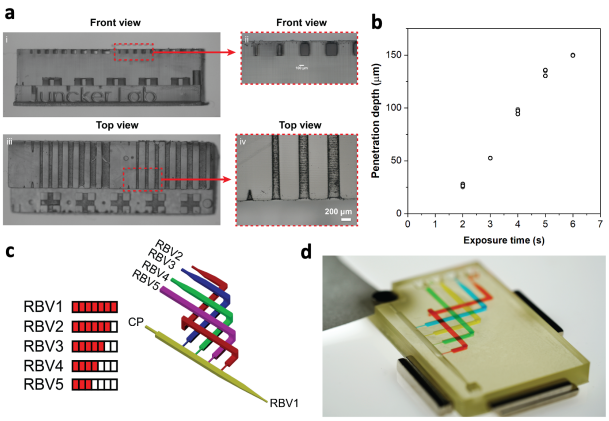

Figure 2: LCD 3D printed features with (a) channel dimensions as low as 126 µm showing the (i-ii) front cross section and the (iii-iv) top view; (b) UV light penetration depth across different exposure times, (c) schematic of embedded microchannels, (d) sequential delivery CC chip.

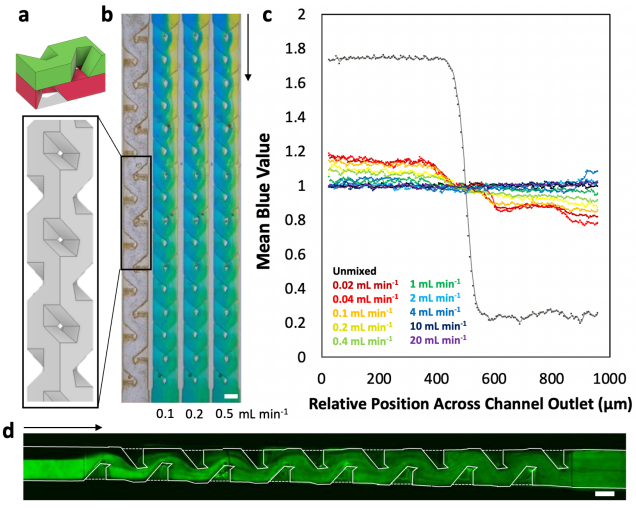

Figure 3: (a) digital rendering of the weaving 3D microstructured mixer, (b) mixing of blue and yellow dyed water, (c) mean normal blue value intensity across the outlet, and (d) mixing of 10 µM fluorescein isothiocyanate at 4 mL min^{-1}. Scale bar: 500 µm, arrow: flow direction.

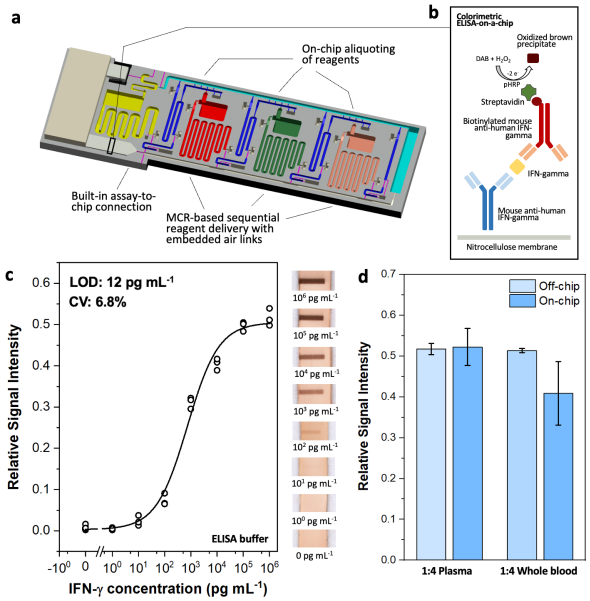

Figure 4: ELISA-on-a-chip for interferon-γ detection showing the (a) ultralow-cost 3D printed device, (b) diagnostic assay design, (c) on-chip colorimetric assay binding curve, and (d) assay readouts in plasma and whole blood.

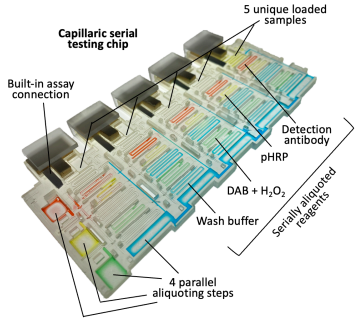

Figure 5: Using the entire build plate, a 5-plex CC ELISA-chip was printed in 45-min for serial testing of 5 samples to generate a diagnostic readout within 45-min from 4 parallel aliquoting steps to supply the entire CC.

REFERENCES

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