Active Stabilization of the Cassie-Baxter State for Long-term Hydrophobicity

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Surfaces submerged in liquid environments for extended periods face severe challenges from biofouling, a critical issue in both marine applications and biomedical engineering. Microorganisms such as bacteria and algae can rapidly colonize materials to form biofilms. In marine settings, this accumulation leads to increased hydrodynamic drag and material degradation, while in medical devices, it causes persistent infections. Although bio-inspired superhydrophobic surfaces attempt to physically isolate liquids and contaminants by maintaining a trapped air layer (the Cassie-Baxter state), this state is inherently metastable. Under continuous hydrostatic pressure fluctuations and gas diffusion, the trapped air plastron inevitably dissolves or collapses. This failure leads to an irreversible wetting transition into the fully wetted Wenzel state, resulting in the complete loss of the surface's anti-fouling properties.

To overcome this thermodynamic limitation, we propose an active engineering solution that transforms the bio-interface from a static boundary into a dynamic, controllable system. We developed a feedback-controlled pneumatic regulation strategy designed to indefinitely sustain the Cassie-Baxter state by actively replenishing the trapped air layer against external pressure variations. The system utilizes a custom 3D-printed dual-chamber test bench enabling precise closed-loop pressure balancing to mechanically prevent liquid penetration.

For experimental validation, we employed high-resolution stereolithography (SLA) 3D printing to fabricate chips with varying hydrophobic micro-textures, see Figure 1(a). Surface optimization using a perfluorodecyltrichlorosilane (FDTS) coating significantly enhanced the intrinsic hydrophobicity, increasing the contact angle from 104° to 144.12°. Preliminary validation using algal solutions demonstrated that the active replenishment system successfully monitored wetting transitions and maintained the air-water interface, as shown in Figuer 1(b). Comparative analysis confirmed that these actively stabilized structured surfaces significantly reduced algal biofilm formation compared to flat controls. This work establishes a new paradigm for infection control, offering a robust, active mechanism to prevent biofouling in long-term submerged surfaces.

(a) (b)

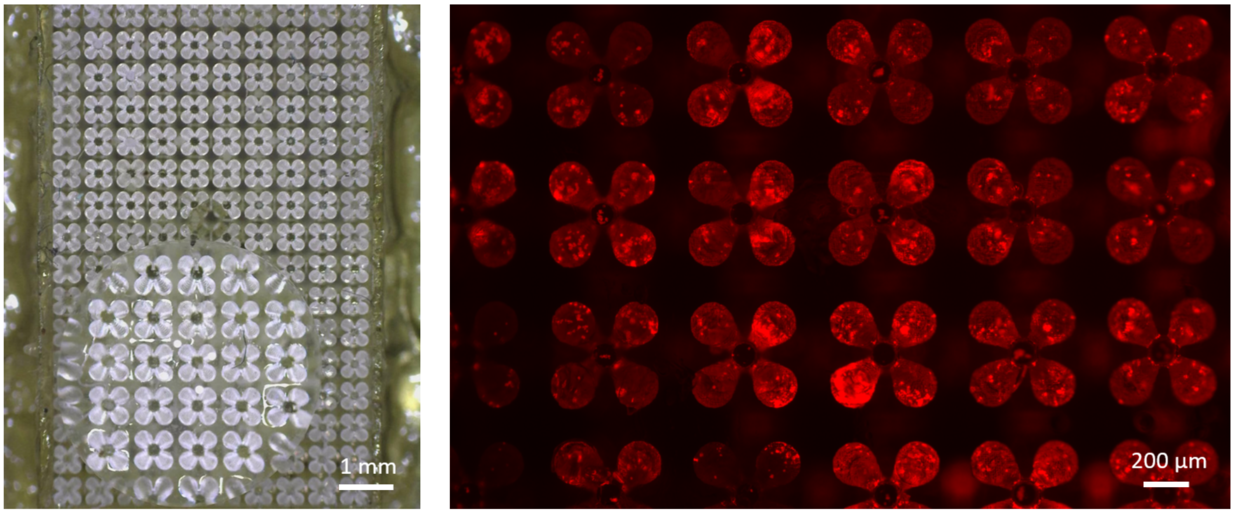

Figure 1: (a) Image of the 3D printed chip and (b) Tested samples covered with algae under fluorescent microscope.