Lab-on-a-Smartphone (LOS): A smartphone-integrated, optoelectrowetting-driven environmental sensor for on-site detection of water quality

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***Abstract*—A lab-on-a-smartphone (LOS) presents a portable environmental sensing tool that enables the monitoring of water quality by performing various detection techniques such as smartphone-integrated fluorescence microscopy and portable loop-mediated amplification (LAMP) assays. The LOS can conduct multiple laboratory functions and has experimentally demonstrated (1) automated on-chip water sample processing, (2) on-site fluorescent detection of harmful algae cells, and (3) fecal contamination of water through LAMP assays. The LOS can overcome conventional labor-intensive and time-consuming techniques for the monitoring of microbiological contaminants in environment waters.**

Keywords—optoelectrowetting; smartphone detection; water quality

I. INTRODUCTION

Water is one of the most important natural resources. A wide variety of species can be found in our water systems, including viruses and bacteria. Some of these aquatic viruses and bacteria can pose immediate threats to human health. Therefore, timely detection and monitoring of harmful pathogens in water systems as well as swift communication of detection information (e.g., signs of contamination and pollution in water systems) with a central host are crucial aspects of proper water quality management [1, 2]. However, conventional techniques for water quality detection have proven to be cost-ineffective, labor-intensive, and inefficient. They require large volumes of water samples and time-consuming inspections with bulky and expensive laboratory facilities [3-5]. To address these issues, a lab-on-a-smartphone (LOS) has been proposed as a smartphone-integrated portable biosensor for environmental water quality management using the emergence of the optoelectrowetting (OEW) technology. Being configured with portable loop-mediated amplification (LAMP) and smartphone-integrated fluorescence microscopy, the LOS enables low-cost, on-site detection of harmful algae cells and waterborne pathogens in environmental water samples to safeguard the public health from the dangers of algae and fecal contamination.

II. METHODS

A. OEW device fabrication and its working principle

The OEW device (Fig. 1a) was fabricated by depositing two ITO electrodes at the edges of the device, followed by a 1.0 µm titanyl phthalocyanine (TiOPc) photoconductive layer, a 1.8 µm aluminum nanoparticle layer and a 1.0 µm Teflon dielectric and hydrophobic layer [6, 7]. After fabrication, the OEW device is placed gently on a smartphone that serves as a portable light source to provide dynamic light patterns onto the photoconductive surface of the OEW device [8]. Using the OEW principle, droplet-based microfluidic functions such as droplet transportation,

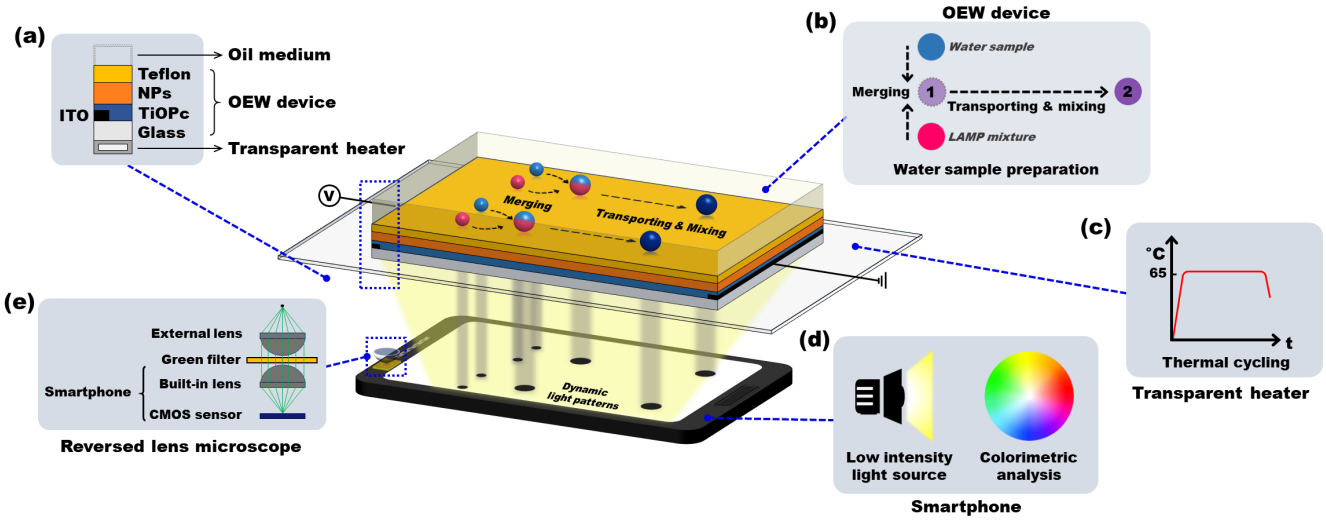

Fig. 1 A lab-on-a-smartphone (LOS) platform for on-site water quality management through portable LAMP testing and fluorescence microscopy.

merging, mixing, and immobilization on a detection zone can be effectively performed for on-chip processing of water samples [9-11].

B. Overview of the LOS and its components

The LOS has been designed as a portable platform that mainly incorporates an OEW device, a transparent heater, and a smartphone. This integrated platform can fully eliminate the need of auxiliary optical and mechanical components (e.g., pumps or tube for reagents delivery, and microscope and CCD camera for fluorescence microscopic analyses) typically required in a conventional lab-on-a-chip (LOC) setup. As shown in Fig. 1, the integrated OEW device performs optical droplet manipulations for on-chip water sample preparations. Secondly, the incorporation of a transparent heater (Fig. 1c) allows the LOS platform to initiate LAMP assays for in-situ analysis of water quality, where isothermal amplification of nucleic acids at 65 °C can be carried out without the need for bulky and costly equipment (e.g., thermal cycler). Furthermore, several features equipped on the smartphone can eliminate the need for other auxiliary equipment and components. Its display screen is utilized as a low-intensity light source to illuminate optical patterns onto the OEW device for light-driven manipulation of water samples. The single-sided open-chamber configuration of the device also allows a smartphone to be easily integrated as a portable optical detector to provide accessibility for on-chip detection of fecal indicator bacteria [12]. Additionally, the smartphone's built-in camera and image processing app can be used to capture snapshots and perform real-time quantitative analyses (via time dependent RGB color changes) of the target water samples respectively during a LAMP reaction (Fig. 1d).

Lastly, a reversed smartphone lens microscope was developed to equip the LOS with the capability for fluorescence microscopy for on-site detection of target cells in environmental water samples (Fig. 1e). It adopted a green bandpass filter inserted between two identical smartphone lens modules to ensure perfectly matched angular field of views due to a full coverage of the smartphone's CMOS sensor [8, 13]. With an attached blue LED light bulb for fluorescent excitation, stained target cells in water samples can be detected by a smartphone's built-in digital camera for up to 45 levels of magnification [8]. Wireless communications and global positioning system (GPS) capabilities offered by the smartphone will then allow captured data (e.g., fluorescence images, location tracking, time of test conducted) to be transmitted wirelessly to a central host (e.g., an environmental regulation agency) for real-time monitoring and management of environmental water quality.

III. Experimental Demonstrations

A. Automated on-chip sample peparation

To demonstrate on-chip sample preparation, Fig. 2 shows video snapshots of two droplets (1.0 µL freshwater containing *E. coli* DNA and a 1.5 µL LAMP mixture) being processed on an OEW device. Another set of two droplets (1.0 µL deionized water containing no *E. coli* DNA and 1.5 µL LAMP mixture) was additionally prepared to serve as the negative control. The four droplets were successfully merged, transported back and forth, and thoroughly mixed when optical patterns were dynamically projected from a smartphone positioned below. During the transportation process, the merged droplets were actuated at an average speed of 1.25 mm/s, where shear forces with the bottom surface created an internal flow to enhance droplet mixing. After completion of the sample preparation, isothermal heating process can begin on the LOS for LAMP amplifications.

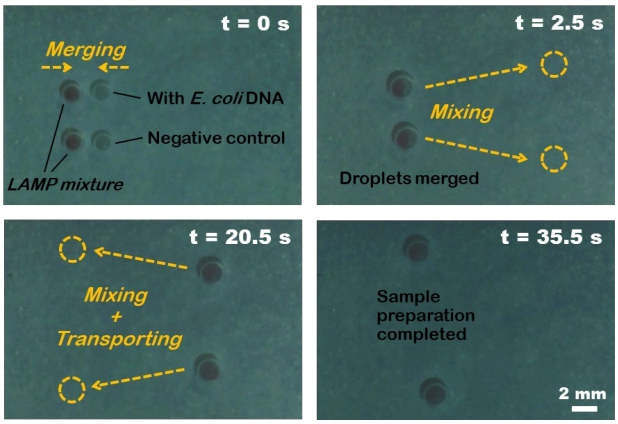

Fig. 2 Experimental demonstrations on an OEW device of the LOS showing automated on-chip sample preparation using a light-driven OEW principle.

B. Detection of fecal contamination in water via LAMP assays

Fig. 3 presents the LOS operating as a portable LAMP platform for on-site monitoring of fecal indicator bacteria in environmental water by initiating the isothermal heating process with the integrated transparent heater. The heater was regulated to provide isothermal heating at 65 °C with an algorithm programmed by the Arduino software. The temperature of the oil chamber of the OEW device was continuously measured and its temperature profile over a 30 min duration (i.e., time taken to complete a LAMP reaction) was plotted in Fig. 3(a). This temperature profile at 65.0 ± 0.25 °C exemplifies the LOS' capability of providing the conditions necessary for successful isothermal amplifications of water samples during a LAMP reaction without using any complex equipment (e.g., thermal cyclers). To experimentally demonstrate LAMP assays on the LOS, snapshots of the water droplets were captured by the smartphone's camera at 10 min intervals throughout the entire LAMP reaction for colorimetric assessment. Real-time color change of the water sample can be clearly observed in Fig. 3(b). To indicate a positive LAMP assay (i.e., a successful DNA amplification), the color of the water droplet is shown to have gradually changed from dark pink to pale yellow. A further quantification of this colorimetric observation was performed via a time-dependent RGB-based assessment using a smartphone's app. The graph in Fig. 3(c) indicated a distinct difference in the droplet's RGB values, thus verifying the successful LAMP amplification of the target DNA sequence [12].

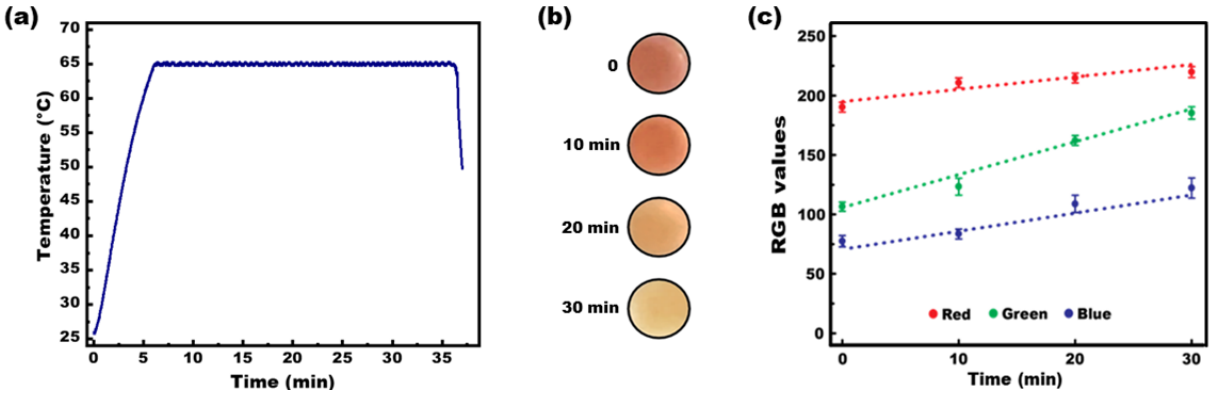

Fig. 3 Experimental demonstrations on the LOS showing its capability for (a) isothermal heating at 65 °C provided by the integrated heater, (b) a successful LAMP assay with visible color change of the target droplet from dark pink to pale yellow, and (c) a quantitative colorimetric assessment with distinct changes in RGB values of the target droplet through the LAMP reaction.

C. Fluorescence microscopy detection of harmful algae cells

To further demonstrate the LOS' capability for fluorescence microscopic detection, another on-chip sample preparation process was conducted by merging and mixing a 5 µL marine water droplet (spiked with *C. closterium* algae cells) and a 5 µL reagent droplet. This reagent droplet contained two vital stains, namely 5 µM of fluorescein diacetate and 2.5 µM of 5-chloromethylflourescein diacetate. The droplet mixing process allows target cells to be stained by the fluorescent dyes before the droplet is being transported and immobilized on the detection zone. The fluorescent signals emitted from the cells will then be detected by the CMOS sensor of the smartphone, and the fluorescence image of the stained *C. closterium* algae cells in the water sample is depicted in Fig. 4(a). The sample preparation process was repeated with another 5 µL marine water droplet (spiked with *Amphiprora* sp. algae cells) and the fluorescence image of the stained *Amphiprora* sp. algae cells in the water sample is depicted in Fig. 4(b). To evaluate the imaging performance of the LOS, a smartphone app was used to count the populations of the target algae cells in each water sample. Fig. 4(c) presents a cell counting comparison between a conventional microscopy approach (i.e., using a hemocytometer) and the LOS. The calculated cell population data show that the LOS can provide comparable results for the target cell counting in the same orders as a conventional microscopy approach [14].

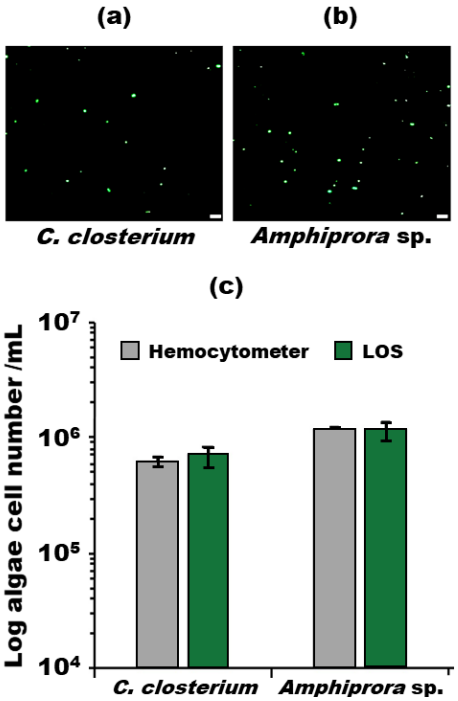

Fig. 4 Experimental demonstrations on the LOS depicting on-chip fluorescent microscopic detection and fluorescence images of marine water samples spiked with (a) *C. closterium* and (b) *Amphiprora* sp. captured by an integrated smartphone. (c) Cell counting comparison showing cell populations in the same orders between a conventional microscopy approach (hemocytometer) and the LOS.

IV. CONCLUSION

The LOS is presented as a low-cost, easy-to-use, portable sensing tool to perform rapid, in-situ monitoring of microbial contaminants in environmental water samples. It is potentially useful for field operations due to its ability to perform automated water sample preparation on an OEW device, using the integrated smartphone as a low-intensity light source for illumination of dynamic light patterns. Then, LAMP assays can be carried out with isothermal heating at 65 °C regulated by the integrated transparent heater. To validate a successful DNA amplification, quantitative analyses of target samples can be conducted with the smartphone's built-in camera and image processing app. Lastly, the LOS can be additionally used to capture fluorescence images of stained target cells in a water sample by adopting a reverse lens microscope. This study offers a environmental sensing tool that is capable of delivering rapid and reliable water quality assessments in resource-limited settings without requiring those time-consuming, labor-intensive equipment or procedures found in existing conventional methods due to the LOS' high sensitivity, ease of use and field-portability.

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