Securing Biochemical Samples Using Molecular Barcoding on Digital Microfluidic Biochips*

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***Abstract*—Microfluidic biochips are being adopted today in point-of-care diagnostics, e.g., COVID-19 testing; therefore, it is critical to ensure integrity of bio-sample before bioassays are run on-chip. A security technique called molecular barcoding was recently proposed to thwart sample-forgery attacks in DNA forensics. Molecular barcoding refers to addition of unique DNA molecules in bio-samples, and the sequence of the added DNA sample serves as a distinct "barcode" for the sample. The existence of the added molecule can be validated using polymerase chain reaction (PCR) and gel electrophoresis. However, this security solution has several limitations: (1) the lack of robustness of the barcode molecules when they are added to other genomic DNA (e.g., samples collected for diagnostics); (2) the need for special bulk instrumentation for validation; (3) the need for human intervention during the overall process. To overcome the limitations, we design a set of robust molecular barcodes that can be validated using both traditional polymerase chain reaction and loop mediated isothermal amplification (LAMP). The validation using LAMP can be executed on a small-in-size and portable digital microfluidic biochip (DMFB). Our LAMP workflow includes a color-changing visual indicator for simple, rapid identification of the barcode existence in solutions. We first demonstrate the proposed security workflow using benchtop techniques. Next, we fabricate a printed circuit board (PCB)-based DMFB with heaters and demonstrate, for the first time, the LAMP assay on a DMFB.**

I. INTRODUCTION

The increasing complexity of bio-protocols has blurred the frontier between the cyber-space (computer-based or human-based control) and biology. Recent studies suggest that interactions across these spaces raise unprecedented security concerns, which create a whole new category of threats known as *cyberbiosecurity threats* [1]. In light of several instances of diverse cyberbiosecurity threats that have been discovered in recent years [2], [3], [4], it is imperative that the trust placed in cyberphysical digital microfluidic biochips (DMFBs)—especially sample integrity—be thoroughly investigated. For example, although accurate COVID-19 testing is critical for preventing the spread of the virus, many test results have been forged by means of replacing the collected bio-samples [5], [6], [7].

Recently, the work in [8] demonstrated benchtop analysis of biochemical-level vulnerabilities and proposed a countermeasure, named *molecular barcoding*. Molecular barcoding refers to adding unique DNA molecules in bio-samples, and the sequence of the added DNA sample serves as a distinct "barcode" for the sample. The existence of the added molecule can be validated using polymerase chain reaction (PCR) and gel electrophoresis. The feasibility of molecular barcoding was demonstrated using benchtop techniques.

However, the security solution described in [8] has several limitations: (1) the lack of robustness of the barcode molecules when they are added to other genomic DNA (e.g., samples collected for diagnostics); (2) the need for special bulk instrumentation for validation; (3) the need for human intervention during the overall process.

To overcome the above limitations, we design a set of robust molecular barcodes. We also propose a simple, yet effective, workflow such that molecular barcodes can be validated using both traditional PCR and loop mediated isothermal amplification (LAMP) [9]. The validation using PCR can be carried out in benchtop settings; on the other hand, the validation using LAMP can be executed on a small-in-size and portable DMFB. The validation using LAMP is simpler and more robust than that using PCR because it does not require high-heat steps during amplification; in fact, it does not need for temperature changes during the assay. Our LAMP workflow includes a color-changing visual indicator for simple, rapid identification of the barcode existence in solutions. We realize the proposed security workflow using benchtop techniques. We also fabricate a printed circuit board (PCB)-based DMFB and demonstrate the security workflow on the DMFB.

The remainder of this paper is organized as follows. Section II describes an overview of background material related to DMFBs and molecular barcoding. Section III presents details of the proposed security workflow. Section IV showcases the proposed workflow using benchtop techniques and demonstrates the effectiveness of the defense. Section V describes experimental results for molecular barcoding on a fabricated DMFB, and presents a security analysis of the molecular-barcoding mechanism. Finally, conclusions are drawn in Section VI.

II. BACKGROUND

In this section, we briefly explain the background material related to DMFBs and molecular barcoding.

A. Digital Microfluidics

A DMFB is composed of a two-dimensional electrode array that manipulates discrete fluid droplets. When driven by a sequence of control voltages, the electrode array can perform fluidic operations, such as dispensing, mixing, and splitting [10]. Because of the precise control over microfluidic operations, DMFBs are employed in lab-on-a-chip systems for high-throughput DNA sequencing and point-of-care clinical diagnosis [11], [12].

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DMFBs manipulate nanoliter droplets using the principle of *electrowetting-on-dielectric* (EWOD) [13]. EWOD refers to the modulation of the interfacial tension between a conductive fluid and a solid electrode coated with a dielectric layer by applying an electric field between them.

B. DNA

Deoxyribonucleic acid (DNA), a molecule that represents the genetic material in all living organisms, is composed of a chain of structures known as *nucleotides*. Each nucleotide can be one of four structures: adenine (**A**), cytosine (**C**), guanine (**G**), and thymine (**T**). The order of the nucleotides forms the identity of a DNA sequence. This sequence forms a single-stranded DNA (ssDNA) that is chemically bonded with another complementary ssDNA; the two ssDNA molecules form a double-stranded DNA (dsDNA), which has a double helix structure. A dsDNA is typically abbreviated as DNA.

C. DNA Amplification Techniques

PCR is widely used to make numerous copies of isolated dsDNA molecules. A unique feature of PCR is that only dsDNA containing the target sequence, referred to as an amplicon, are copied ("amplified"), with the aid of a specific set of chemical reagents as well as precisely controlled thermal cycling [14]. During amplification, the two strands of dsDNA are thermally separated in a higher temperature, e.g., 95 °C. Next, under a lower temperature (e.g., 55 °C), each single strand is allowed to re-attach (anneal) to specially synthesized primers that have complementary nucleotide sequences. A DNA polymerase enzyme then extends the primer sequence by filling in the remainder of the complementary nucleotides at around 72 °C, thus, constructing new copies of a target dsDNA. By repeating this process (i.e., thermal cycling and primer re-attachment), thousands of new copies of an amplicon can be generated.

Agarose gel electrophoresis is used to validate the existence of the amplicons after PCR. Amplicons are size-separated using an electric field; negatively charged DNA molecules migrate toward an anode (positive) pole. Hence, DNA molecules are separated based on their molecular weight, which is proportional to the size of DNA strands [15]. The shorter the amplicon (i.e., the lower the molecular weight), the further the sample will reach on the gel.

LAMP is a highly specific, efficient, and rapid DNA amplification assay based on Bst polymerase activity [9]. In contrast to PCR that requires thermal cycling, LAMP is carried out at a constant temperature, e.g., 65 °C. Four to six different primers are typically used to amplify six distinct regions on the target gene, which increases specificity [9]. As shown in Figure 1, the target DNA is synthesized with six distinct regions F1, F2, F3, B1, B2, and B3. The complementary ssDNA for a region is named using a suffix 'c', e.g., the complementary region of F1 is named F1c. Six primers, namely two outer primers (oligonucleotides of F3 and B3), forward internal primer (FIP), backward internal primer (BIP), loop forward primer (LF), and loop backward primer (LB), are added to the target DNA. During amplification, the specially designed primers result in short "dumbbell" structures that form seeds for exponential LAMP amplification. This LAMP dumbbell structure contains multiple sites for initiation of synthesis from the three prime ends of the open loops and annealing sites for both the inner and loop primers. As amplification proceeds from these multiple sites, the products grow and form long concatemers, each with more sites for initiation. Therefore, the amount of DNA produced in LAMP is considerably higher than in PCR-based amplification.

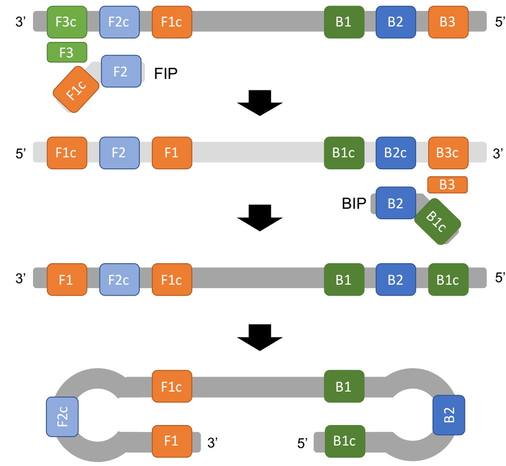

Fig. 1: LAMP uses primers recognizing six distinct regions of target DNA [9].

The amplification product can be detected based on the pH change resulting from amplification reactions performed with minimal buffering capacity [16]. During amplification, when a DNA polymerase incorporates a deoxynucleoside triphosphate into the nascent DNA, the released by-products include a pyrophosphate moiety and a hydrogen ion [17]. The released products change the pH value of the solution. If a pH indicator (e.g., pH-sensitive dye) is added with the LAMP solution, we are able to distinguish if DNA molecules are being amplified by observing the color change of the solution, e.g., pink to yellow. Using this detection method, molecular diagnostic tests can be analyzed immediately without the need for specialized and expensive instrumentation. Due to its simplicity, ruggedness, and low cost, LAMP has been demonstrated as a simple screening assay in several point-of-care diagnostics, such as detecting infectious diseases of tuberculosis [18], malaria [19], and SARS-CoV-2 [20].

D. Molecular Barcoding

To defend against sample-forgery attacks in DNA forensics, a multi-space security scheme was proposed in [8], where molecular barcodes are added to the collected samples. In the first step of the multi-space scheme, a trusted party designs a set of barcodes with varying lengths and develops barcode-specific primers. These barcodes and the associated primers are registered in a secure database along with their secret identification numbers. In the second step, authenticated collectors obtain the barcodes and their associated secret identification numbers. A molecular barcode can be added in two possible ways. In the first approach, sample tubes are pre-loaded with a barcode solution. The sample tubes are taken into the field, and then the crime-scene evidence is added directly to the tube with a sterilized swab. Alternatively, collection tubes could be

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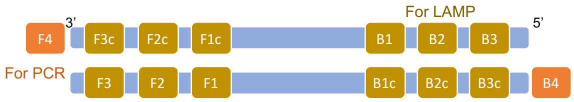

Fig. 2: Molecular barcode that can be amplified by LAMP and PCR.

prepared with lyophilized barcode(s), which would increase the stability of the barcode while in the field [21]. In the meantime, authenticated analyzers receive primers and their secret identification numbers. In the third step, a collector communicates with an analyzer by sending two types of material: 1) a barcoded DNA sample (biological material), which encapsulates a secret molecular barcode obtained from the trusted party; 2) a public key-encrypted message (information material), which includes secret information about the barcode and the sample identification numbers. After completing the identification routine, the analyzer can verify the genuineness of all the collected DNA samples.

III. Robust Molecular Barcoding

Although the [8] showed that molecular barcoding is effective in defending against sample-forgery attacks using benchtop techniques, the existing molecular-barcode design has several key drawbacks: First, the experimental results shown in [8] suggest that the barcode primers may anneal on other genomic DNA within the solution (e.g., human genomic samples) and thus amplify unwanted DNA segments. The unintended amplicons may result in false positives or false negatives in the outcome, therefore undermining the effectiveness of molecular barcoding. Second, the proposed scheme requires bulk instrumentation for validation. As molecular barcoding is designed to secure samples in the field, such as DNA fingerprinting in forensics, the need for the instrumentation might not be practical in real-world scenarios. Finally, the demonstrated molecular-barcoding process is not automated, and therefore the analyzer needs to be trustworthy, which might not always be realistic. To overcome these drawbacks, we propose a robust design methodology for molecular barcoding.

The newly designed molecular barcode is illustrated in Figure 2. We first design a "unique" DNA sequence that cannot be found within the human (or any naturally-occurring organisms) genome. Because the sequence is unique, when we run PCR or LAMP, the barcode primers do not anneal on the genomic DNA (bio-sample), i.e., no unwanted amplicons in the outcome. Next, we design the LAMP primers associated with the DNA sequence using the tool provided by New England Biolabs Inc. [22]. The tool generates the amplification sequence (shown as blue in Figure 2) as well as the specific regions for LAMP (shown as brown in Figure 2). Based on the specific regions, inner primers and loop primers are also determined. To validate the existence of the barcode, the LAMP primers and a master mix solution are first added to the solution. Next, the mixture is situated at an isothermal instrumentation. After 10 to 30 minutes, we are able to see the color change in the mixture, which indicates amplicon existence.

Note that the barcode is designed in a unique way such that it can also be validated using PCR. We design extra sequences at both ends of the barcode and two primers that can be annealed at these regions. Similar to [8], the barcode can be amplified using these two PCR primers and validated using agarose gel electrophoresis.

IV. Benchtop Demonstration

In this section, we show the effectiveness of the newly proposed barcode using benchtop techniques in both PCR and LAMP settings.

A. Molecular Barcodes

We synthesized four DNA barcodes whose sequences are unique in that they are not found in the humane genome. The four barcodes are named as Barcode1, Barcode2, Barcode3, and Barcode4. The sequences of the four barcodes as well as the associated PCR primers are shown in Table I. We next design primers for LAMP using the NEB Primer Design Tool [22]. The LAMP primers of the four barcodes are shown in Table II.

B. PCR Experiments

We show that the barcodes can be amplified using PCR and that the barcode characteristics (fragment size) can be identified using gel electrophoresis. We also show that the barcode can be amplified with the existence of genomic DNA.

Experiment Design: The experiment was designed by considering seven parallel PCR reactions. In Reaction 1, 1 ng of human genomic DNA (Roche, 11691112001, 100 µg/500 µL, 349 bp) was used as a control. In this reaction, we should not observe any result when barcode primers are added. In Reactions 2-5, four barcodes of 7.5 pg were added to the tubes. We expect to see the barcode characteristics when the corrected primers are added to the reactions. In Reaction 6, Barcode1 and genomic DNA were added to the tube. In this reaction, we should see the results of both the genomic DNA as well as the barcode when the associated primers are added. Finally, we used H_2O as the negative control in the experiment.

We ran this experiment twice: 1) we added the barcode primers into the tubes and ran PCR; 2) we added the genomic-DNA primers (GAPDH) into the tubes and ran PCR.

PCR Reaction and Gel Electrophoresis: We placed the tubes in a thermal cycler, and the thermal conditions were as follows: 1) 95°C for 2 min, 2) 30 cycles at 95°C for 30 sec, at 55°C for 30 sec, at 72°C for 1 min 30 sec, and 3) 72°C for 10 min. After PCR program was completed, PCR products were evaluated on the 1.1% agarose gel. Figure 3 shows the results obtained by gel electrophoresis. The results show that the barcodes can only be amplified using the right primers; when genomic primers are added, we do not see any amplicons. These results also show that the barcode can be amplified even the genomic DNA is present in the mixture. Likewise, the genomic DNA can be amplified even in the presence of the barcodes.

C. LAMP Experiments

We show that the barcodes used in the previous PCR experiments can also be amplified using LAMP.

Sample and Reagent Preparation: To run LAMP, we used a WarmStart Colorimetric LAMP 2x Master Mix with UDG typical LAMP protocol (NEBM1804, Ipswich, USA). We prepared the primer mix using the following concentrations: 2 µM

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TABLE I: The sequence information for the barcodes. PCR-primers are indicated in green.

Barcode1 (267 bp)	GTA CAC TCT TTC CCT ACA CGA CGC TCT TCC GAT CT TGT AAG GAC CGC CGC TTT CGC TCG GGT CTG CGG GTT ATA GCT TTT CAG TCT CGA CGG GCT AGC ACA CAT CTG GTT GAC TAG GCG CAT AGT CGC CAT TCA CAG ATT TGC TCG GCA ATC AGT ACT GGT AGG CGT TAG ACC CCG TGA CTC GTG GCT GAA CGG CCG TAC AAC TCG ACA GCC GGT GCT TGC GTT TTA CCC TT AGA TCG GAA GAG CAC ACG TCT GAA CTC CAG CAC TG
Barcode2 (310 bp)	GTA CAC TCT TTC CCT ACA CGA CGC TCT TCC GAT CT CAA TGA TAG GCT AGT CTC GCG CAG TAC ATG GTA GTT CAG CCA ATA GAT GCC TAG TAC GCT GAC GGC ATT CAG AGT ACG CTG ATC GGC TTA TGA CGT ATG TGA CGC AGC TCT TAG CGC AAT GTA TGT GCT GTT ATC GAA GCC TAT GGC TGA GTA TGT AAC GCT ATG GCG TGC TAG TCG TCT CAT ATA CGT CTG ATG ACC TCG TAT CAT GTT ATA GGG CTG CGA ACT GTC GAT GAT GGT CAC AGA TCG GAA GAG CAC ACG TCT GAA CTC CAG CAC TG
Barcode3 (370 bp)	GTA CAC TCT TTC CCT ACA CGA CGC TCT TCC GAT CT CGA GAG ATG TTT GTA GGT GCG GAA TGT GTG CGG TCT ACC TTA GCT GTA GTG TGC GAT GAA CCT ACA CAC AAC GTG GTA TAG TGG CCG ATC TTA GAG TGA TCC TAT CAC TCC TTA CGC ACC AGA AGG GAT CTG CAT ACC AGG CGG AGA ACT TGG AAG GCG GCT AGA TCA CTG AAT TGC GGG AAT CGG CAT TTC GCA TTC TTA GGA TCT AAA CCT TAG ACC TCC GCG TGC GAT TGC ACC TGC TTG GTA CAG AGT TAC AAG CCC CCC GCA CTT TCT TTG CGG TCG TTA AGA GGG AAA TCG CCC AGA TCG GAA GAG CAC ACG TCT GAA CTC CAG CAC TG
Barcode4 (430 bp)	GTA CAC TCT TTC CCT ACA CGA CGC TCT TCC GAT CT TTT ATT GGT ACG TAA TTT CGT CAA CCG TTT TTC GGT CTA ACT TCT TAA TGA CTT CTG TAA TTA ACT TTA CCG CGT TTT CAT AAT CAT CAC GAT GCA GCA TGG CCG CGT GCG TAT GAA TGT AGC GGG TTG CAA TGG TAA TGG ACA GCG CAG GAA CGC CAT TTG CCG TCA AAT GGA TGG CAC CCG AAT CAG TTC CGC CGC CGG CAA TGG CAT CAA ATT GGT ACG GAA TGC CGG CTT CCT CCG CAG TGG CTA CAA CTG CAT CGC GCA AAC CTT TGT GAG AGA CCA TGG ATG CAT CGT AAA CGA TAA TCT GCG GGC CTT TGC CCA TTT TGC TCT GCG CTT CCT TCT CGG AAA TGC CAG GCG TGT AGA TCG GAA GAG CAC ACG TCT GAA CTC CAG CAC TG

of each outer primer (F3 and B3), 16 µM of each inner primer (FIP and BIP), and 4 µM of each loop primer (LF and LB).

LAMP Reaction: We show that a barcode can only be amplified using its associated primers. In this experiment, we prepared a total of 16 tubes; each barcode was added to four tubes, respectively. The tubes were multiplexed with all four primer mixes. For example, barcode 1 was added to tubes 1, 5, 9, and 13, and four different primer mixes were added to these four tubes, respectively. Similar to the previous experiment, after mixing all reagents, the tubes were transferred to the hybridization oven and incubated at 65 °C for 30 minutes. The results of this experiment are shown in Figure 4. We see that only the tubes that consist of barcode and its associated primers turned yellow from pink, i.e., barcodes were amplified in these tubes. The other tubes remained pink after 30 minutes.

TABLE II: The sequence information for the LAMP-primers.

Barcode	Primer	Length	Oligonucleotides
Barcode1	F3	19	GGGTCTGCGGGTTATAGCT
	B3	19	CTGGAGTTCAGACGTGTGC
	FIP	40	GCCGAGCAAATCTGTGAATGGC TTTCAGTCTCGACGGGCT
	BIP	41	TACTGGTAGGCGTTAGACCCCG AGGGTAAAACGCAAGCACC
	LF	22	GCCTAGTCAACCAGATGTGTGC
	LB	17	TGACTCGTGGCTGAACG
Barcode2	F3	20	GCGCAGTACATGGTAGTTCA
	B3	20	GTGTGCTCTTCCGATCTGTG
	FIP	39	GCGCTAAGAGCTGCGTCACAT CGCTGACGGCATTCAGAG
	BIP	41	TAACGCTATGGCGTGCTAGTCG ACCATCATCGACAGTTCGC
	LF	19	CGTCATAAGCCGATCAGCG
	LB	23	TCTCATATACGTCTGATGACCTC
Barcode3	F3	18	TCTGCATACCAGGCGGAG
	B3	20	AGTTCAGACGTGTGCTCTTC
	FIP	41	GCACGCGGAGGTCTAAGGTTTA AACTTGGAAGGCGGCTAGA
	BIP	42	TTGCACCTGCTTGGTACAGAGT GGCGATTTCCCTCTTAACGA
	LF	18	GCGAAATGCCGATTCCCG
	LB	17	TACAAGCCCCCCGCACT
Barcode4	F3	18	GCACCCGAATCAGTTCCG
	B3	19	GACGTGTGCTCTTCCGATC
	FIP	42	CGCGATGCAGTTGTAGCCACTG CGGCAATGGCATCAAATTGG
	BIP	40	ACGATAATCTGCGGGCCTTTGC TACACGCCTGGCATTTCC
	LF	17	GAAGCCGGCATTCCGTA
	LB	20	CCATTTTGCTCTGCGCTTCC

V. Molecular Barcoding using a DMFB and Security Analysis

We show, the first time, that LAMP can be carried out using a DMFB.

A. *Experimental Setup*

Fabricated DMFB: We designed a PCB-based DMFB for the experiment, and fabricated the biochip using services available at [23]. The DMFB contains 66 electrodes, four reservoirs, and three heating regions; see Figure 5(a). Reservoir modules are placed on the top and bottom sides of the biochip, and the

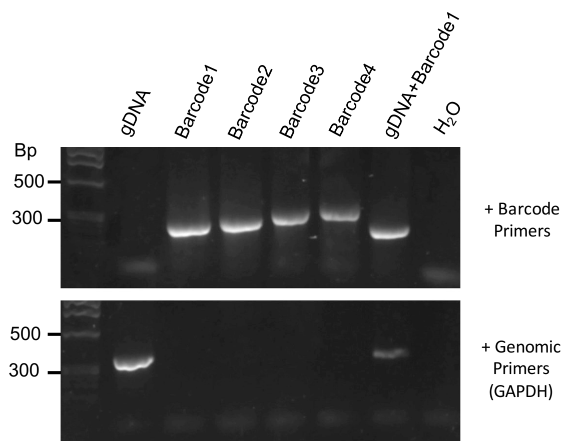

Fig. 3: Results of DNA amplification for the PCR reactions.

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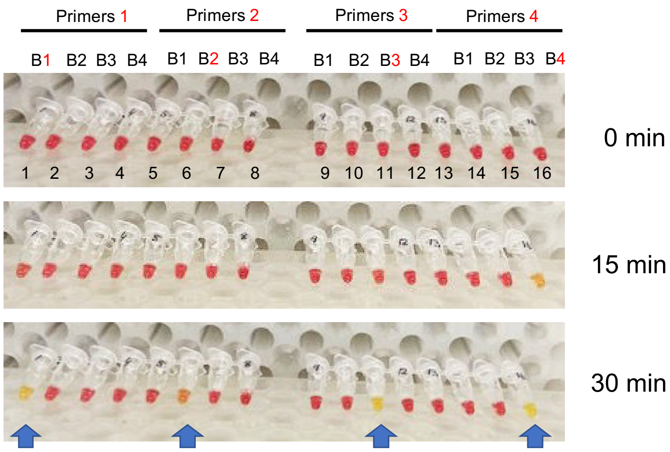

Fig. 4: Results of the LAMP assay.

modules can dispense different reagent droplets. Three $60\,\Omega$ resistors are soldered on the back of the biochip, and each can emit 1 W power; see Figure 5(b). The control signals associated with the electrodes and the heaters come from the pin heads that are soldered on the boundary of the PCB. An ITO glass coated with Cytop is used as the top plate to ground on-chip droplets.

Control PCB: For the fabricated DMFB, the activation/deactivation status of the electrodes is controlled by a low-voltage-to-high-voltage converter (Part No. Microchip HV507); see Figure 5(c). In addition to the electrode-activation circuit, three relay high-current relays (Part No. Panasonic AQW212) are used for heater control. Each high-current relay IC is controlled by a configuration bit, and these configuration bits are stored in the register IC (Part No. Texas Instrument SN74AHC595). Besides these ICs, two pin-header modules (shown within the red rectangles) are used as the DMFB socket, which allows DMFB replacement on the control board.

Overall system: The hardware setup used to operate the DMFB is shown in Figure 5(d). The DMFB is installed above the control board using the pin-header socket. A micro-computer (Part No. Raspberry Pi 4) on the left generates control signals to the control board, and a PID controller is installed in the micro-computer. An amplifier board and the functional generator are used to generate three voltage sources: 1) a source of 50 Hz and 200 V for electrode actuation, 2) a source of 12 V for heaters, and 3) a source of 3 V for the ICs.

A camera module and an IR sensor (Part No. Panasonic AMG8833) are placed on top of the DMFB to capture droplet conditions and provide the thermal feedback, respectively. Figure 6(a) shows a heat-map captured by the IR sensor. The thermal feedback is utilized by the PID controller for maintaining the desired thermal conditions. The heating module can reach $65\,°C$ within a minute; see Figure 6(b).

B. Experimental Results

We executed the LAMP assay on the fabricated DMFB. A sample mixed with the barcode was validated using the associated primers and the LAMP master mix. As a negative control, another sample that does not contain any barcode was added to the primers and the LAMP master mix. After the mixing was completed, the two droplets were transported to the heater module on the DMFB; see Figure 7. The two droplets were heated to $65\,°C$. After 20 minutes, we can clearly see that the sample with the added barcode changed its color from pink to yellow, indicating that the barcode has been amplified. On the other hand, the sample without any barcode remained pink during heating, since no barcodes were amplified.

C. Security Analysis

To attack the molecular-barcoding scheme, an adversary needs to forge a fake barcode that meets the following two constraints: 1) it must use the same primers as those for the legitimate barcode so that the forged barcode will be amplified using PCR (or LAMP) in the analysis; 2) the forged barcode must have the same length as the legitimate barcode so that the gel-electrophoresis results of the forged barcode are the same as that of the legitimate barcode. The work in [8] showed that the probability P_{pmr} that an attacker can successfully guess a primer is $P_{pmr} = P(L_p) \cdot P(S|L_p)$, where L_p is the event that the attacker guesses the right primer length, and S is the event that the attacker guesses the right nucleotide order. To guess one of the primers in this work, $P_{pmr} \leq 2.24 \times 10^{-12}$. Because a robust barcode in this work contains of a total of eight distinctive primers, the probability of guessing all the primers correctly is $(P_{pmr})^8 < 6 \times 10^{-98}$. Therefore, it is unlikely that an attacker can discover the molecular barcode.

VI. Conclusion

As microfluidic biochips are being adopted for point-of-care diagnostics, it is critical to ensure bio-sample integrity even before bioassay execution. Molecular barcoding has been proposed recently to thwart sample-forgery attacks. We have presented a robust design methodology for molecular barcoding, where the barcodes can be amplified by both PCR and LAMP. We have demonstrated the effectiveness of the proposed barcodes using benchtop techniques. While molecular barcoding using traditional PCR can be easily carried out on benchtop settings, we showed, for the first time, that molecular barcoding can be validated using LAMP on a fabricated DMFB. The results of LAMP were easy to observe because the workflow includes a color-changing visual indicator. This research opens the door for point-of-care diagnostics using LAMP and microfluidics.

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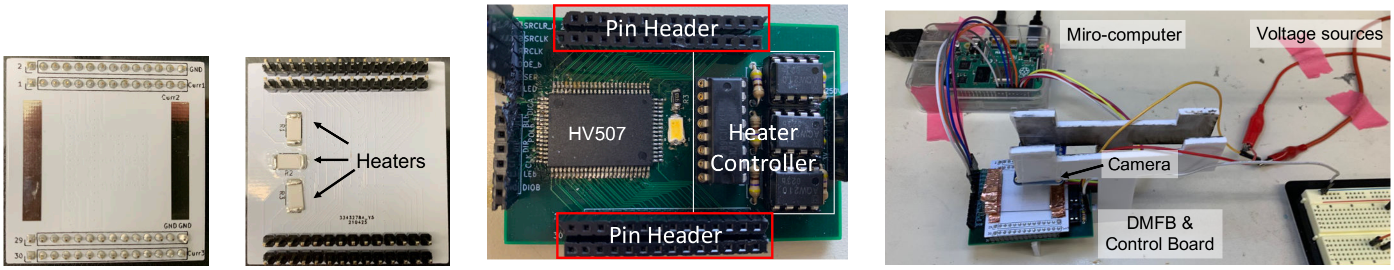
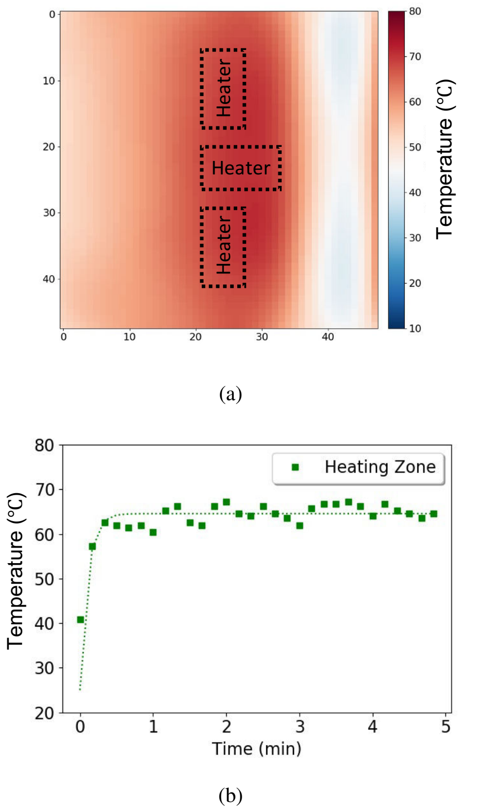


(a) (b) (c) (d)

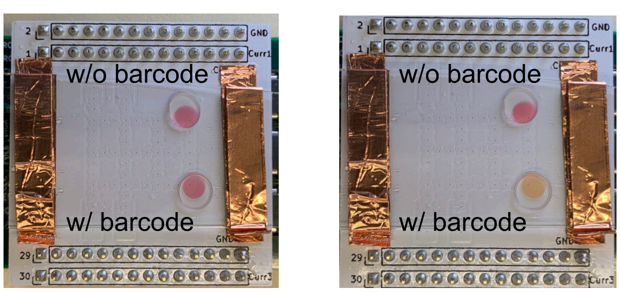
Fig. 5: (a) The front of the fabricated DMFB. (b) The back of the fabricated DMFB. (c) The control board for the DMFB. (d) The experimental setup.



(a)

(b)

Fig. 6: (a) The heat-map captured by the IR sensor. (b) The increase in temperature with time.



0 min 20 min

Fig. 7: LAMP on a fabricated DMFB.

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