WIRELESS VALVING FOR CENTRIFUGAL MICROFLUIDIC PLATFORM USING FIELD FREQUENCY MODULATION

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ABSTRACT

This paper reports a selective wireless active valve mechanism for a centrifugal microfluidic compact disk operated using field frequency modulation techniques. The reported technique offers a further advancement in the centrifugal microfluidic field by enabling full control on the liquid flow. The localized and selective RF wireless heating of paraffin wax active valves was utilized to control the liquid flow in centrifugal CD. Vacuum/compression valve (VCV) and mixing applications are also demonstrated in this work. Experimental characterization shows valve operational is within ~100 s of activation using a radio frequency power of 1 W, at a speed of 200 rpm. The reported technique offers a further advancement in the centrifugal microfluidic area by enabling full control on liquid flow.

INTRODUCTION

Over the past few decades, centrifugal microfluidic compact disc (CD) devices have been an active research area of microfluidics in lab-on-a-chip systems. This is attributable to their advantages over conventional fluidic platforms, including the low costs of fabrication, and their relatively small in size. The valves are considered among the most important components in a microfluidic CD device, mainly due to their function, which is to control the fluid movement inside the network of the microchannel. The valves can be categorized based on their working principles such as capillary, hydrophobic, siphoning, centrifugal-pneumatic and active valves. The active valve is an interesting research area that merits further exploration, owing to their ability to control the liquid flow in the microchannel by external means during operation. Various mechanisms have been reported for the active valve system, including paraffin wax [1], hydrogel [2], pneumatic [3] and frozen liquid [4].

Among this list, the paraffin wax has a high potential to be used as an active valve, mainly due to its low cost, biocompatible features and the fact that it can be activated by heating the wax above its melting temperature, which is slightly above room temperature (i.e. 40 ºC). There are several studies in the literature reported to have used paraffin wax as an active valve by utilizing various sources of heat such as lasers, infrared (IR), and hot air. A composite wax-based microvalve has been reported to operate by a single laser source [5]. Although the response is fast, it involves a complicated setup where the CD needs to be stopped in order for the wax to be positioned and heated. A method using a pure paraffin wax without a filler is presented in [6]. They demonstrate a novel active valve technique whereby the paraffin wax is actuated using focused IR radiation. However, in this method, a high powered IR source is needed compared to previous methods. In addition, these valving techniques [5], [6] could contaminate the sample/reagent, as the wax is mixed with the liquid during actuation. An improvement of this drawback is reported by using VCV [7] utilizing paraffin wax. Despite this, a hot air source is needed to melt the paraffin wax. Moreover, both hot air sources and IR [6], [7] must expose their thermal sources along the radial line of the disc that restricts localized activation of the valve, exposing heat to another part of the disc. This would contribute to the unnecessary heating of the sample/reagent nearby the valve.

This study aims to address the localized heating issue of the paraffin wax active valve for microfluidic CD applications using RF wireless heating. A selective wireless active valve mechanism for centrifugal microfluidic CD operated using field frequency modulation techniques is reported. The VCVs technique by using this method and mixing applications is demonstrated; as is the thermal characteristic of the microfluidic CD during the operation. The proposed technique offers a further advancement in the body of literature on centrifugal microfluidics by enabling full control on the liquid flow.

DEVICE PRINCIPLE AND DESIGN

The developed device utilizes a planar inductor-capacitor (LC) resonant circuit as a heater to heat up the paraffin wax plug in a microfluidic CD (Figure 1a). The heater is activated when it was exposed to an RF field with a frequency (f_m) that matches the resonant frequency (f_r) of the heater transmitted by the antenna [8]. This induces an electromotive force in the coil of the heaters, thus providing Joule heating due to the current and resistance in the coil. The heating is maximized when the f_m matches the f_r, which gives a good selectivity to activate the heater by tuning f_m. More than one heater can be selectively and simultaneously activated by designing heaters with various f_r, and modulating f_m to the corresponding f_r values in a time-sharing manner (Figure 1b). The proposed method allows the integration of a heater's array on a microfluidic CD, thus providing the

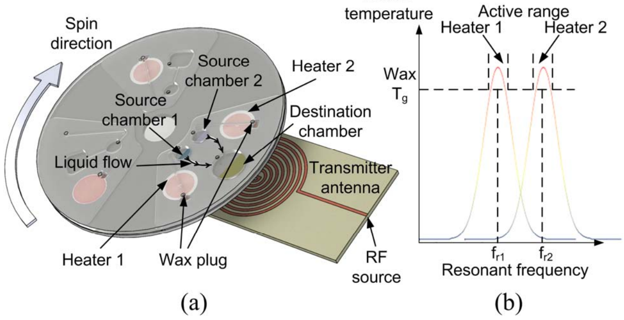

Figure 1: The working principle, (a) conceptual diagram of the device, (b) selective control of frequency sensitive wireless heater.

advantage of localized temperature control for selective valve activation.

To demonstrate the wireless control of the paraffin wax active valve, VCV, proposed by Al-Faqheri *et al.*, is employed [7]. The microfluidic CD consists three sets of the microfluidic systems to demonstrate the wireless activation of VCV (i.e. a compression valve, a vacuum valve, and a mixing application utilizing two vacuum valves) (Figure 2). The VCV is implemented by applying a small amount of paraffin wax into the venting holes of the source/destination chamber that is located on top of the heater. The fluid is unable to flow out from the source chamber due to the system's vacuum/compression condition. The microchannels have a width and depth of 0.7 mm and 1.0 mm, respectively; while the radius of the source chamber is 3 mm, is and able to hold ~ 29 µL of liquid.

Due to the centrifugal pressure, the liquid in the destination chamber is propelled from the center toward the edge of the microfluidic CD during spinning. However, the liquid would be unable to flow because the paraffin wax restricts the air passage within the microchannels. When the heater is activated, the paraffin wax which melts and creates an air flow through the venting hole. This subsequently allows the liquid to flow from the source to the destination chamber.

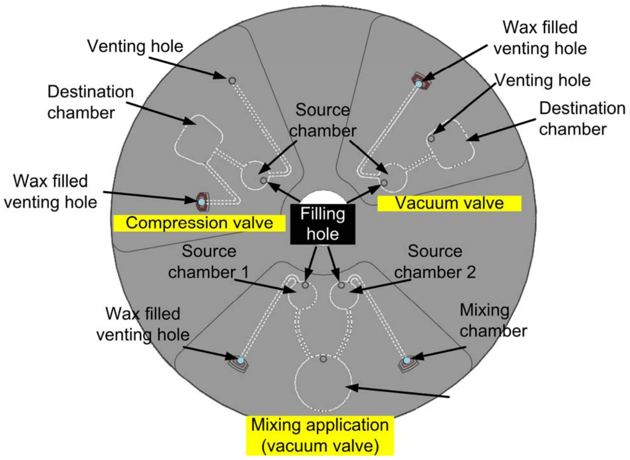

Figure 2: Microfluidics and chambers design on a compact disc shows vacuum/compression valve and mixing application.

FABRICATION

Figure 3a illustrates the microfluidic CD fabrication. The CD was designed using computer aided software, and was constructed using two layers of polymethyl methacrylate (PMMA), with a thickness and diameter of 1.4 mm and 90 mm, respectively. Both layers were bonded with a double-sided pressure-sensitive adhesive (PSA) (ARcare® 8939, Adhesives Research, PA, USA). The micro-scale feature (channels and chambers) on the top layer and the heater's slot on the bottom layer of PMMA are engraved using a Computer Numerical Control machine. The stencil cut-out on the PSA with both patterns of the layer was removed using a vinyl cutter (Silhouette CAMEO®, UT, USA). The heater, which is composed of Cu-clad Polyimide (PI), is placed

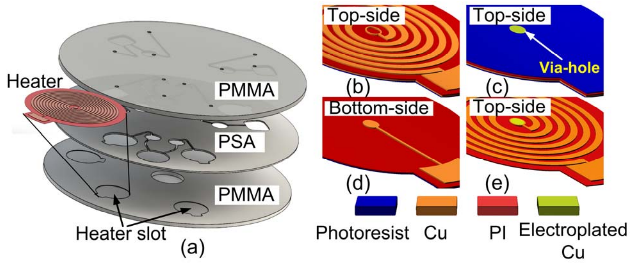

Figure 3: (a) 3D model illustration for fabrication of microfluidic CD and the location of the heater, (b) to (e) shows heater fabrication process according to sequence.

into the heater's slot of the bottom PMMA layer designed to be beneath the venting hole. All layers then were aligned and bonded together to create a microfluidic CD with an overall thickness of ~3 mm, consisting of a compression valve microfluidic unit, a vacuum valve microfluidic unit, and a mixing microfluidic unit.

Figure 3b-e shows the fabrication process of the wireless heater. The heater is fabricated using a double-sided Cu-clad PI film (Flexbase™ Copper Polyimide Laminate G1860, Sheldahl, MN, USA), with ~35 µm and ~25 µm thick Cu and PI layers, respectively. The photolithography is performed using a dry-film photoresist (Platemaster PM240, DuPont™, DE, USA).

Firstly, the top-side features that consist of a coil and a capacitor plate are formed by wet etching one side of the layer a patterned photoresist as a mask (Figure 3b). Next, Cu electroplating was performed at the via-hole to create an electrical connection between the top and bottom copper layers. The electroplating process is performed at a current density of 29 mA/cm^2 for 20 min (Figure 3c). Finally, the bottom-side of the capacitor plate is formed by wet etching Cu using the patterned photoresist as a mask to complete the heater.

EXPERIMENTAL RESULTS

The f_r for the heaters fabricated were first evaluated using a network analyzer (Hewlett Packard 4396B). The result presented in Figure 4 shows dips at f_{r1} ~ 151 MHz and f_{r2} ~ 137 MHz, which correspond to f_r for Heater 1 and Heater 2, respectively.

Thermal response

An experiment was first conducted to investigate the heating profile of the device. The experimental setup employed in study is shown in Figure 5. An output signal was generated from an RF signal generator (8648A, Agilent Technologies Inc., CA, USA). The signal was amplified to 1.0 W using an RF power amplifier (TVA-R5-13, Mini Circuits, NY, USA) connected to a planar transmitter antenna located ~1 cm below the CD. The CD was spun at 200 rpm using a DC motor, where, simultaneously, the heater (Heater 1 was used for this test) was activated by tuning f_m from the RF signal generator to match f_{r1}. Figure 6a shows a thermal image captured using an IR thermal camera (VarioCAM®, Jenoptik, Dresden, Germany) during spinning after 2 min of heater activation. The figure shows that only the area nearby the heater was heated, while the temperature of the other region on the CD remained unaffected. This result

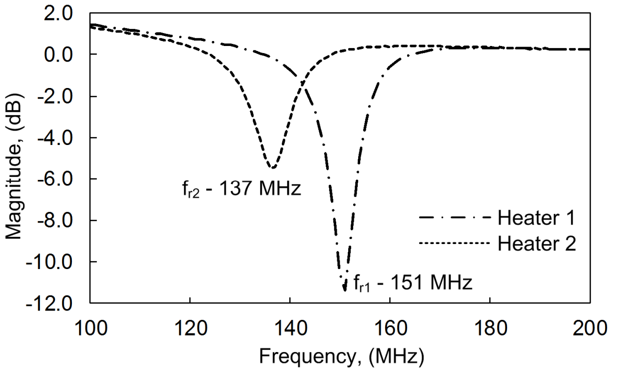

Figure 4: Reflective coefficient, S_{11} measurement for both, Heater 1 and Heater 2.

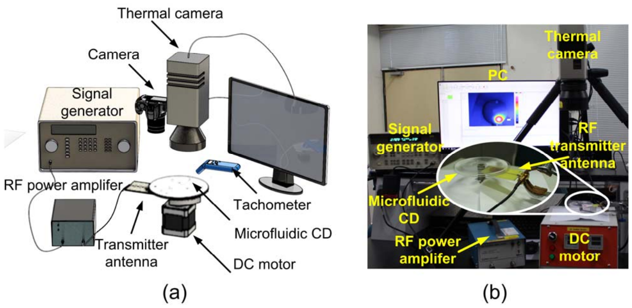

Figure 5: (a) The illustration of the experimental setup, (b) the actual experimental setup.

verifies the effectiveness of the localized heating using RF wireless heating on a microfluidic CD application.

The device tests were also conducted to investigate the thermal behavior with respect to the rotational speed of the CD. The CD was spun at a different speed, starting from 200 rpm to 1000 rpm, with a step size of 100 rpm. The heater was activated for 2 min. The CD was then stopped, and the thermal image was immediately captured. Figure 6b shows the result for this test. The graph in the figure shows that the temperature of the heater region is inversely proportional to the rotational CD speed. This is possibly due to the amount of time of the heater is exposed to the RF field frequency during each rotation. As the speed of the CD increases, the RF exposure to the heater decreases. The highest temperature of 42 ºC was attained when the rotational speed was 200 rpm, which is sufficient to melt the wax.

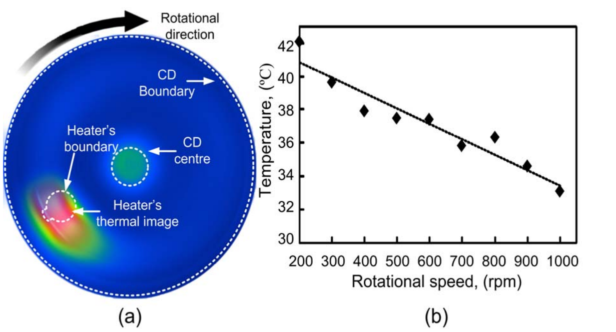

Figure 6: (a) Thermal image of the microfluidic CD with activated heater during operation; (b) graph of temperature vs. *speed and the trend line.*

Wireless VCV Test

Preliminary wireless tests for the device were experimentally performed using the setup shown in Figure 5. The venting holes for the vacuum and compression valves equipped with wireless Heater 2 (f_{r2} = 151Mhz) were loaded with paraffin wax (Sigma-Aldrich, MO, USA); while the source chamber was filled with 20 µL – 25 µL of red colored deionized (DI) water. Next, the CD was spun at 200 rpm, and simultaneously, the heater was activated with 1 W of RF power and an fm that matches f_{r2}. The process images were captured every 1 s using a camera that is controlled using the MATLAB® software. Figure 7a and 7b show the images during the tests for the vacuum and compression valve microfluidic unit, respectively. According to the images, the DI water started to flow to the destination chamber through the microfluidic channel, due to the centrifugal force at 95-97 s, after activation of the heaters. This indicates that the paraffin wax started to melt; this can be observed from the magnified image of the venting holes (bright spot showing the molten wax). The total operation time for the DI water to be totally transferred to the destination chamber was 100-102 s after the activation of the heaters.

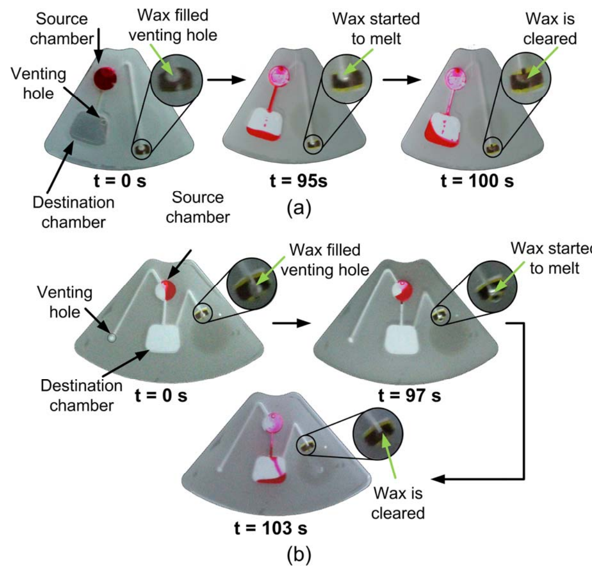

Figure 7: The wireless demonstration of (a) vacuum valve; and (b) compression valve.

Mixing Demonstration

A further test was conducted using two heaters to activate two different valves in order to demonstrate a mixing application. The source chambers 1 and 2 were loaded with 25 µL of Hydrochloric Acid (HCl) (37%; RCI Labscan Ltd., Bangkok, THA) and Bromothymol Blue (BTB) sodium salt solution (0.04 wt.%; Sigma-Aldrich, MO, USA), respectively. Heater 1 (f_{r1}) and Heater 2 (f_{r2}) were positioned at their respective locations to activate the valves. The CD was spun at 200 rpm, followed by the activation of Heater 2 by tuning f_m to f_{r2} with 1 W of RF power. Based on Figure 8a, the BTB was completely transferred to the mixing chamber within 138 s. The magnified images (t = 138) show a clear view of Heater 2's capacitor plate, indicating that the wax in valve 2 has been dispersed out from the venting holes due to the centrifugal force, while the wax in the valve 1 remained intact. Then the Heater 1 is activated by tuning f_m to f_{r1} with the same RF power. The HCl was transferred to the mixing chamber for 100 s of heater activation. The liquid in the mixing chamber, which was blue (BTB) in color, turned to a yellowish color, suggesting that the HCl has been transferred out to the mixing chamber. Figure 8a also shows that there is no sign of wax in valve 1. The overall process took 238 s for both liquids to be mixed, as shown in the experiment timeline in Figure 8b. The time required for melting the wax in valves 1 and 2 was experimentally verified prior to the mixing application. More time was required for valve 2 because the heater used in this valve has a lower quality factor that contributes to the low power transfer efficiency, compared to Heater 1, which possessed a higher quality factor.

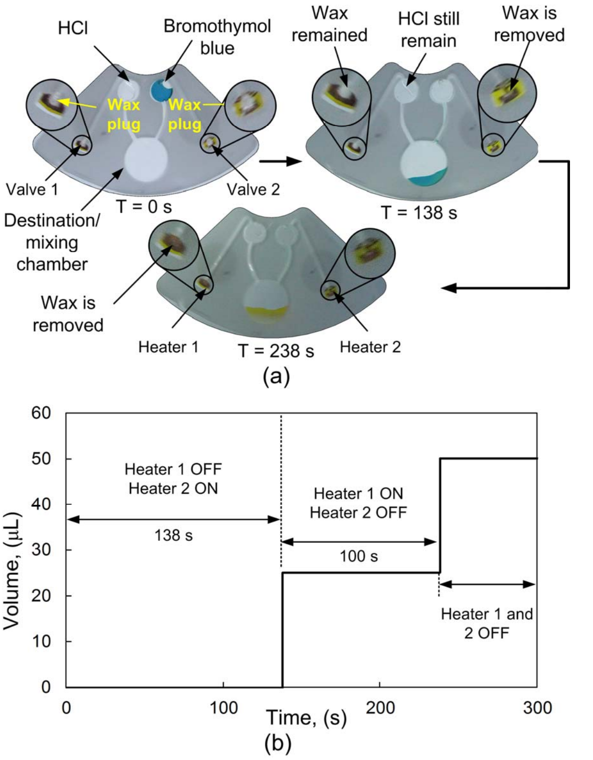

Figure 8: (a) Selective control of vacuum valve for mixing application; (b) graph volume in destination chamber vs. *time for the mixing application.*

CONCLUSION

This paper demonstrated a novel wireless RF controlled active valve for a microfluidic CD platform using field frequency modulation. The valve was activated using an LC resonant circuit. This served as frequency-sensitive wireless heaters that were activated only when resonated by external RF fields were produced, using a transmitter antenna. The LC heater was used to heat up the paraffin wax in the microfluidic CD. The thermal response of the device proved localized heating of the microfluidic CD with a temperature up to 42 ºC at the speed of 200 rpm. The VCV activation by using the proposed method took 100 s for the liquid to complete the flow from the source to the destination chamber. The selective operation of the heater has been successfully implemented in a mixing application using HCl and BTB, where the results demonstrated the feasibility of activating multiple heaters. The proposed method offers a further advancement in the literature on microfluidic research by enabling full control on liquid flow in a wireless manner, aiming to provide a solution to power centrifugal microfluidic devices.

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