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Wirelessly Addressable Heater Array for Centrifugal Microfluidics and *Escherichia Coli* Sterilization

Xing Chen, Lele Song, Babak Assadsangabi, Jie Fang, Mohamed Sultan Mohamed Ali, *Member*, *IEEE*, and Kenichi Takahata, *Member, IEEE*

***Abstract*— Localized temperature control and heater interface remain challenges in centrifugal microfluidics and integrated lab-on-a-chip devices. This paper presents a new wireless heating method that enables selective activation of micropatterned resonant heaters using external radiofrequency (RF) fields and its applications. The wireless heaters in an array are individually activated by modulating the frequency of the external field. Temperature of 93 °C is achieved in the heater when resonated with a 0.49-W RF output power. The wireless method is demonstrated to be fully effective for heating samples under spinning at high speeds, showing its applicability to centrifugal systems. Selective sterilization of *Escherichia coli* through the wireless heating is also demonstrated. Healthcare applications with a focus on wound sterilization are discussed along with preliminary experiments, showing promising results.**

I. INTRODUCTION

Microfluidics and lab-on-a-chip (LOC) technologies are bringing innovations to healthcare and biomedical areas. LOC devices consist of many different micro-scale components including chambers and interconnection channels, valves, pumps, and sensors, depending on the applications [1]. The microheater is another core element that has been used to control chemical reaction as well as valving and pumping on a chip. Many heaters used in microfluidics are typically micropatterned resistors, in which electrical currents passed through them are converted to thermal energy [2]. However, microfluidic devices integrated with heater arrays require numerous on- and off-chip lead wires in order to individually power the heaters and achieve different temperatures and thermal gradients, which also require complicated control modules. These requirements inevitably increase the complexity, size, and cost of a microfluidic system as it is scaled up and needs increased number of thermal steps. The centrifugal microfluidic platform has been studied to utilize centrifugal forces for fluid manipulation with simple set-ups while eliminating the need for external syringe pumps [3]. In addition to pumping of liquids, many other functions have been integrated on the platform, including passive valving, decanting, calibration, mixing, metering, sample splitting, and fluid separation. However, electrical powering and interface to the spinning microfluidic platform remains a challenging issue. The difficulty is further deteriorated when the integration level rises. This type of centrifugal systems typically uses external heaters to heat up the whole device in order to perform a thermal process [4]. This poses inherent problems in selective and local temperature control on the platform, limiting the processing ability of the systems. To address these issues, wireless heating methods based on infrared [5], microwave [6], and induction heating [7, 8] have been reported. These approaches, however, have various practical challenges, including precise temperature control, dependence on properties of fluid within the fluidic channels, miniaturization, and incompatibility with standard planar microfabrication techniques. Another critical issue with these wireless methods is that they do not offer the selectivity in the activation of multiple heaters embedded in a microfluidic system. This selectivity is essential for the wireless heating approach, because individual microheaters in the system usually need to achieve different temperatures and heating timings to perform a controlled thermal process in the fluidic chamber with which each heater is coupled.

This paper reports a new wireless heating method and technology suitable for centrifugal microfluidics and other LOC applications (Fig. 1). The heat production is enabled by the frequency modulation of external radiofrequency (RF)

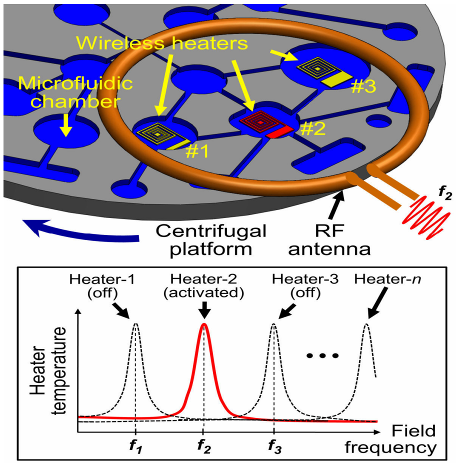

Figure 1. Wireless activation of micro resonant heaters integrated into centrifugal microfluidics. In this example, only Heater-2 is activated using an RF field by tuning its frequency to the resonant frequency of the heater (f_2), while the other heaters are off. Simultaneous operation of multiple heaters is possible through the field frequency modulation that mixes the different frequencies corresponding to the resonant frequencies of selected heaters.

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X. Chen, B. Assadsangabi and K. Takahata are with the Department of Electrical and Computer Engineering, The University of British Columbia, Vancouver, BC V6T1Z4, Canada (phone: +1-604-827-4241 fax: +1-604-822-5949; e-mail: takahata@ece.ubc.ca).

L. L. Song is with Michael Smith Laboratories, The University of British Columbia, Vancouver, BC V6T1Z4, Canada.

J. Fang is with Department of Chemistry, The University of British Columbia, Vancouver, BC V6T1Z1, Canada.

M. S. Mohamed Ali is with Faculty of Electrical Engineering, Universiti Teknologi Malaysia, 81310 Skudai, Johor, Malaysia.

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magnetic fields, realizing selective activation of multiple planar heaters embedded in microfluidic devices. Wireless heater arrays are demonstrated for selective wireless heating of samples under spinning conditions. This device also displays promising characteristics in the sterilization of *Escherichia coli* toward healthcare and therapeutic applications. The developed devices are thin, flexible, and potentially low cost and disposable, offering attractive features for biomedical and LOC applications.

II. WORKING PRINCIPLE

The wireless heating principle is based on frequency-sensitive induction heating that utilizes a micropatterned resonant circuit as the wireless heater, which is integrated into microfluidic devices as illustrated in Fig. 1. An RF magnetic field at a selected frequency is generated using an external antenna and radiated towards the heaters, each of which is a printed inductor-capacitor (*L*-*C*) circuit that uses a spiral coil as the inductor. The field induces RF electromotive force and current in the coil of each circuit. Joule heating occurs in the coil most effectively when the field frequency matches the resonant frequency of the circuit, providing a strong selectivity in the heater activation enabled simply by field-frequency tuning. As each of the heater circuits is designed to have a different resonant frequency, multiple heaters can be selectively and simultaneously activated through the frequency modulation technique [9]. This ability allows one to integrate an array of the heaters on a centrifugal microfluidic platform or a LOC to perform temperature control at specific locations in a fully wireless manner, offering a potential solution to wiring issues in these microfluidic technologies.

III. DESIGN, FABRICATION, AND CHARACTERIZATION OF WIRELESS HEATERS

For characterization and demonstration purposes, proof-of-concept devices of the wireless heater based on the planar *L*-*C* circuits were developed with various designs that provided resonant frequencies ranging from 57 MHz to 295 MHz. Arrays of these heater circuits were fabricated using single-sided copper-clad polyimide film with 50-µm thickness. A lithographic process combined with copper electroplating was performed to fabricate the arrays, using a well-established method [9]. The fabricated devices were coated with a 15-µm-thick Parylene-C for both electrical and biological insulations. A sample device and a cross-sectional view of the single heater are shown in Fig. 2. The heater circuits in this particular device have the coils with an identical pattern and size (6 turns, 3.8×4.5-mm^2 overall size, 100-µm line width) that theoretically provides a common inductance of 95 nH. Different resonant frequencies are assigned to these circuits by varying the size of the parallel-plate capacitors coupled with the coils. Because the substrate is flexible polyimide film, the device is deformable while providing high thermal insulation through the substrate. In addition, since the device is a printed passive circuits (just like RFID tags), it is possible to be produced with low costs.

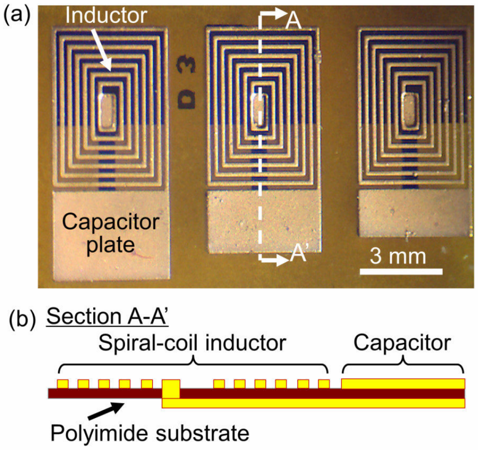


Figure 2. (a) A sample of fabricated wireless heater array. The heaters in this array were measured to have the resonant frequencies of (from left to right) 231 MHz, 264 MHz, and 295 MHz. (b) A cross-sectional view of the single heater circuit.

The frequency responses of the fabricated heater devices were characterized by scanning the frequency of the external field radiated to the heaters over their resonant frequencies (with a fixed RF output power of 100 mW). Temperatures of the heaters during this frequency scan were recorded using an infrared (IR) camera (VarioCam HiRes 1.2M, Jenoptik AG). Fig. 3 displays a phase dip observed through a reader antenna inductively coupled with one of the tested heaters, which represents the resonance of the heater, and IR images of the heater that was excited at different field frequencies. It can be seen that wireless heating is highly sensitive to the field frequency. As also can be seen in the IR images, the heater coils exhibit temperature gradients, with the highest at the center region of the coil. The overall heating level depends on the output power fed to the excitation antenna. For example, the heater generated temperatures of 57 °C at the center of the coil and 35 °C at its edges when wirelessly resonated using a 320-mW output power with a ~1-cm distance between the antenna and the heater. The peak temperature at the coil's center reached 93 ˚C when the output power was increased to 488 mW.

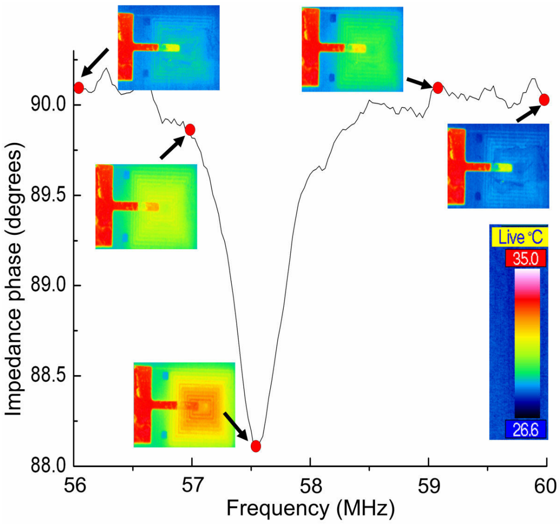
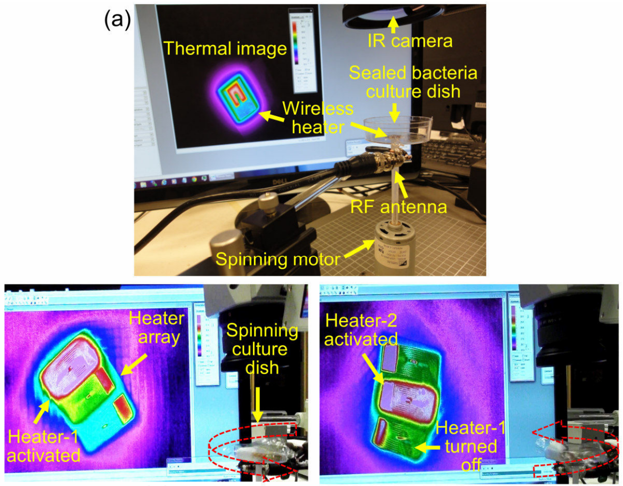


Figure 3. The resonance of a sample wireless heater (at 57.6 MHz in this example) shown as a phase dip detected using an external antenna inductively coupled with the heater's coil (measured using an Agilent 4396B impedance analyzer). Insets are IR images of the heater excited at different field frequencies, showing strong heat production upon the resonance.

IV. EXPERIMENTAL RESULTS

A. *Selective Wireless RF Heating of Spinning Devices for Centrifugal Systems*

To evaluate the feasibility of the developed technique and device for the application to a variety of centrifugal systems, the experimental set-up shown in Fig. 4(a) was prepared. In this set-up, a DC motor spun a sealed culture dish in which a heater array was located, and the external antenna was placed below the dish (with a distance of ~1 cm) to excite the array under spinning using an RF power of 320 mW. The IR camera was held above the set-up to capture thermal images of the spinning array. For proper thermal imaging, the maximum spinning speed was limited to 300 rpm in this test. Heating behaviors were observed to show no detectable difference between the cases with and without spinning. The selective activation of the spinning heaters was successfully performed through the frequency modulation method described earlier (Fig. 4(b) and 4(c)). These results suggest that the developed wireless heating method is applicable to rotating samples at the above spinning speed at least, a promising potential path to enabling precise control of microheater arrays integrated in centrifugal microfluidic devices.



(b) (c)

Figure 4. (a) The wireless heating set-up for characterization of spinning samples; (b) real-time IR images of a rotating heater array, showing that different heaters were wirelessly activated.

B. *Targeted Sterilization of E. Coli*

To prepare test samples, *E. coli* cultured in LB Broth medium was evenly smeared onto the LB agar culture dishes. The dishes were then incubated at 37 °C for 8 hours. After this, two wireless heaters that had different resonant frequencies were introduced into the dish, which was then sealed. One of the heaters was to locally apply heat to *E. coil* onto the agar layer, and the other heater was a control. To turn on the former heater, an RF field, with the frequency aligned to the resonant frequency of the heater, was radiated to the dish (Fig. 5(a)). This radiation did not activate the control heater due to the mismatch between the field and heater frequencies. As the first step, the heaters were made direct contact with the agar surfaces, and the active heater was heated up to 67 ˚C at the coil's center region for 30 minutes. This thermal stimulation was followed by additional incubation at 37 °C for 1-3 hours to further grow *E coli.* In this sample, no bacteria colony was found in the entire area of the activated heater, whereas the region of the control heater was fully covered by the bacteria, showing that the wireless heating process sterilized the bacteria with a high spatial selectivity. However, the agar medium appeared to have shrunk due to dehydration. In order to avoid this artifact, caused due to the direct heat transfer to the agar, and to quantify a spatial density of bacteria colonies formed in different regions, a piece of polyimide mesh (1×1 mm^2 grid size, fabricated by lithography and etching) was inserted between the agar layer and the heaters. The thickness of this mesh was made to be 50 µm, thin enough to ensure that temperature on the agar was close to that of the heater. Similar sterilization results were observed in this setting as well under the same wireless heating condition (Fig. 5(b) and 5(c)). In another test, the peak temperature on the heater (at its center) was reduced to 55˚C (by lowering the RF power). In this case, spatial gradients of *E. coli* growth, presumably caused by the temperature gradient on the heater, were clearly observable as shown in Fig. 6 – there was no *E. coli* colony around the coil's center region, and its density increased as the location moved towards the periphery of the coil. Fig. 6(b) also indicates that 55 °C was high enough to fully sterilize *E. coli*.

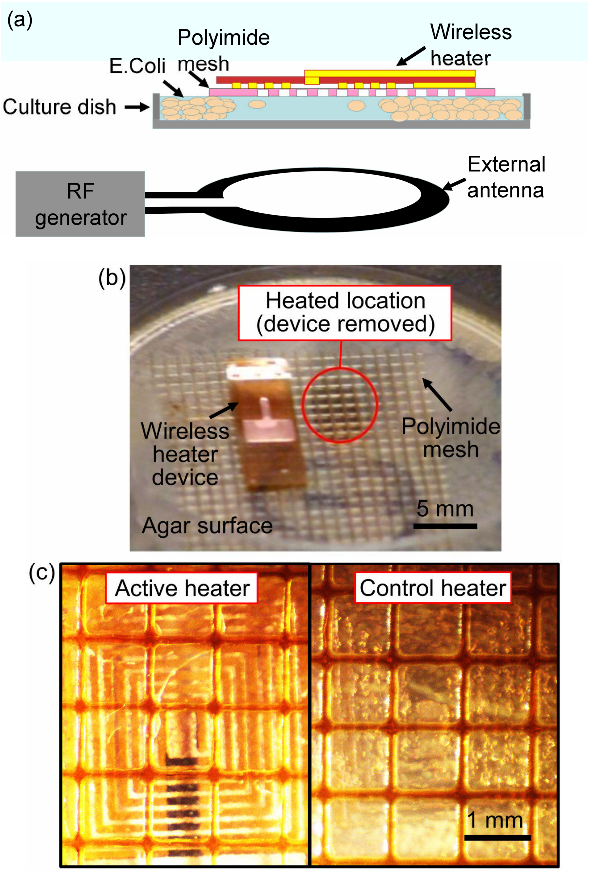


Figure 5. (a) The setup for wireless *E. coli* sterilization experiments; (b) the agar layer (covered by the polyimide mesh) shows cloudy color caused by the bacterial growth everywhere except the wirelessly heated region (at 67 °C) that remains transparent; (c) a comparison of the agar layers (the mesh located on top) shows that the agar remains clear on the active heater (the pattern of the coil located below the agar is clearly visible) whereas *E. coli* grew on the entire area of the control heater (blurring the coil pattern).

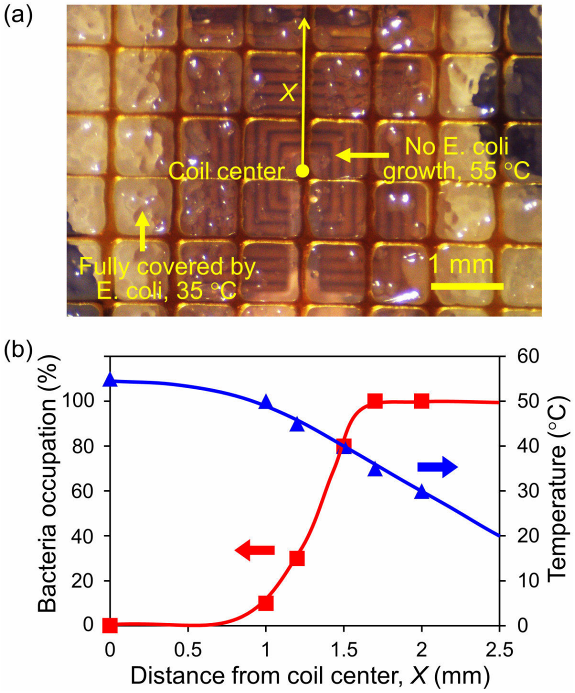


Figure 6. (a) A typical sterilization result for the case that the peak temperature of the heater was 55 °C; (b) the distribution of *E. coli* grown colonies and corresponding temperatures measured across the heater coil.

C. *Wireless RF Sterilization for Healthcare Applications*

The successful results of bacteria sterilization suggest possible applications of the wireless heating technique and device for therapeutic and sanitary purposes. One potentially promising area is the sterilization of wounds and their dressing products. Infection of wounds induced by bacterial growth considerably impairs their healing process [10]. The thin, flexible, and low-cost nature of the wireless heater could allow the heaters to be embedded in wound dressings or adhesive bandages and activated to sterilize the wounds, preventing infections and assisting their healing. To experimentally verify the feasibility of the concept, an array of the wireless heaters covered by an adhesive bandage was wrapped around a finger and exposed to the RF field with controlled frequencies (Fig. 7(a)). The selective activation of the heaters was successfully implemented under this device condition in which the array was deformed into a three-dimensional form (Fig. 7(b)). The result suggests that this application concept is viable and encourages further developments.

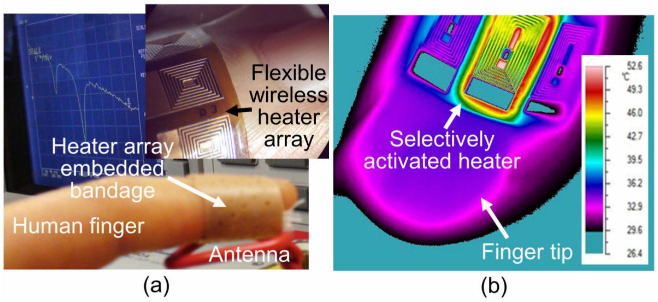


Figure 7. (a) A wireless heater array covered by an adhesive bandage wrapped around a finger (different resonant peaks detected from the array are shown on the analyzer's monitor, and inset image shows the array without the bandage); (b) IR image of the fingertip showing selective wireless heating.

V. CONCLUSION

The wireless RF control of micropatterned resonant heaters has been studied for microfluidic and biomedical applications. Printed passive *L-C* circuits served as frequency-sensitive wireless heaters that were activated only when resonated by the external fields produced using an excitation antenna. The microfabricated wireless heater showed high frequency selectivity, and the RF output power was adjusted to achieve targeted levels of heater temperature. The selective operation of the heaters arranged in an array was demonstrated under both stationary and spinning conditions toward the applications for centrifugal microfluidics and lab-on-a chip systems. The wireless heating method was also found to be highly effective for *E. coli* sterilization, providing a novel path to spatial and temporal control of heating for bacterial studies that can be performed in fully sealed dishes. The heater devices are flexible and potentially low cost and were experimentally demonstrated to be fully functional under bent conditions. These results suggest many application opportunities in healthcare fields as well, including sterilization of wound dressings and local thermal therapies.

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