An acoustothermal heater for paper microfluidics towards point-of-care glucose detection

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Abstract

We report the first observation of acoustothermal heating of wet papers under high frequency vibrations. The proposed heating method utilizes acoustic absorption of cellulose fiber, which exhibits viscoelastic properties. The surface acoustic waves propagate on the piezoelectric substrate and refract into a wet paper strip on the substrate. The refracted longitudinal waves deliver acoustic energy into the wet paper by vibration damping in the form of heat. Acoustothermal heating was discovered to be frequency-dependent and to reach local maxima at certain frequencies. Based on this finding, we developed a paper-based microfluidic heating system for point-of-care glucose detection.

Keywords: surface acoustic wave; acoustic absorption; viscoelasticity; paper-based microfluidic heating system; glucose detection

1. Introduction

We report the first observation of acoustothermal heating of wet papers under high frequency (~MHz) vibrations as a follow-up study of our previous research on the acoustothermal heating of PDMS (Ha et al., 2015). The heating mechanism utilizes acoustic absorption of cellulose fiber networks, which show viscoelastic behaviors. In order to generate acoustic waves and couple them with wet papers, a conventional surface acoustic wave (SAW) system was adopted. The SAWs propagating on the piezoelectric substrate readily refract into a piece of wet paper placed on the substrate, deliver acoustic energy into the paper, and in turn heat it by vibration damping. Based on this finding, we developed an acoustothermal heating system for paper-based microfluidics specifically aimed to promote and accelerate chemical reactions involved with heating. Our heating system provides rapid (exceeding 500 K/s),

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volumetric heating of the wet paper strip. Moreover, the heater provides a disposable platform as the heater and the paper strip that are coupled by reversible bonding. A portable heating system can be built as a point-of-care (POC) device when operated with a palmtop electronic driver circuit powered by a CR123 battery (Rezk et al., 2014).

2. Working mechanism

2.1. Viscoelasticity

Governed by Hooke’s law, an ideal elastic material instantaneously responds to an applied stress whereas an ideal viscous material shows stress proportional to strain rate. In reality, all materials exhibit both viscous and elastic behaviors, and the intermediate property between them is called viscoelasticity. Noticeable characteristics of viscoelastic materials are wave attenuation and phase lag between stress and strain when cyclic loading applied, resulting in mechanical energy dissipation (Lakes, 2009). Typical materials with a large viscoelastic response are polymers, biological materials and metals at high temperature. Of various viscoelastic polymers, cellulose is the most abundant natural polymer, whose long chain consists of numerous β-linked D-glucose units. A filter paper composed of cellulose fibers is manufactured from pulps obtained by decomposing hemicellulose and lignin bound in wood into water-soluble molecules, which can be easily cleansed. Therefore, the filter paper exhibits viscoelastic behaviors due to the fibrous networks of the viscoelastic cellulose.

2.2. Acoustic absorption

An incident wave attenuates while propagating through a medium. The acoustic absorption, which is the conversion of incident wave energy to heat, is the primary wave attenuation mechanism in viscoelastic materials. Unlike ideal elastic and viscous materials, whose stress and strain are in phase (0°) and 90° out of phase respectively, the strain response lags behind the stress applied with a lagged phase angle δ in a viscoelastic material, as shown in Fig. 1(a). The viscoelastic properties can be described with complex modulus $E^*$ and loss tangent $\tan \delta$. The complex modulus is defined as $E^* = E' + iE''$ where $E'$ and $E''$ are the storage and loss moduli, respectively, and the loss tangent is defined as $\tan \delta = \frac{E''}{E'}$, which is a measure of acoustic absorption. As shown in Fig. 2(b), the SAWs propagating on the piezoelectric substrate (LiNbO$_3$) readily refract into a piece of wet filter paper, delivering acoustic energy into the wet filter paper in the form of leaky SAWs at the interface between the LiNbO$_3$ substrate and the water layer bound in the filter paper. The longitudinal leaky SAWs in turn heat the viscoelastic cellulose fiber networks by vibration damping.

![Fig. 1](image.png)

Fig. 1. (a) Stress and strain versus time (in arbitrary units) of viscoelastic materials under cyclic loading; (b) Acoustic absorption of a wet filter paper placed on the LiNbO$_3$ substrate.
Fig. 2 (a) Temperature increase of wet papers over the frequency range from 5 to 55 MHz with error bars indicating the standard deviation from five independent experiments; (b) Acoustothermal heating of a 5 μl water droplet (A) and a filter paper with 5 μl water (B) by SAWs produced by a split IDT with a frequency of 8 MHz. The 2D temperature profiles of the same region (dashed circle) were measured by an infrared camera.

3. Results and discussion

The acoustothermal heating of wet papers by SAW-induced vibration damping was found to be frequency-dependent. When the period of the repeated AC signal accords with a relaxation period of the cellulose fibers networks, the acoustothermal heating of the viscoelastic paper hits a local maximum. In order to identify the most energy-efficient frequencies for heating, we measured loss tangent (tanδ), the ratio of the energy dissipated to energy loss per cycle. In this sense, the loss tangent is proportional to the energy absorbed and thus the temperature increase such that tanδ ~ ΔT. Therefore, the loss tangent of the wet filter paper can be calculated by measuring the temperature increase when actuated with SAWs generated by a slanted IDT (SIDT) whose working frequency ranging from 5 to 55 MHz, as shown in Fig. 2(a). From the measurements, the temperature increase at 8 and 29 MHz was identified to reach a local maximum at which the most efficient wave energy absorption occurs. Thus, we can conclude that the most energy-efficient acoustothermal heating of wet filter papers can be achieved by SAWs at these frequencies.

Figure 2(b) shows the 2D temperature profile comparison of a water droplet and the same amount of water confined in a filter paper, actuated by SAWs with a frequency of 8 MHz at room temperature over 10 s, to verify the heating of viscoelastic filter papers. As shown in Fig. 2(b), the filter paper directly affected by SAWs was rapidly heated (exceeding 500 K/s) with a temperature increase of above 60°C and stabilized in a few seconds, whereas the temperature increase of the water droplet alone was only 20°C. The rapid, volumetric, simple, inexpensive, portable and disposable acoustothermal heating system developed in this study can be employed to accelerate and promote chemical reactions involved with heating for point-of-care diagnosis. As a heating platform for paper-based microfluidic point-of-care diagnostic devices, it can be utilized in a variety of applications such as health diagnosis, food testing, environment monitoring, etc. As shown in Fig. 3, glucose detection tests using Benedict’s reagent, which is a simple and inexpensive glucose detection method, was performed to verify the applicability of the proposed heating platform in paper microfluidics. The filter paper strips wet with Benedict’s reagent (light blue) and glucose solution were placed on a 29 MHz split IDT and heated by acoustothermal heating. When the fluid samples were heated, red precipitates formed, indicating the presence of glucose in the samples. With the preliminary results, we have shown that the proposed paper microfluidic heating system can potentially be utilized as a paper-based microfluidic heating system for POC glucose detection.
4. Experimental

The proposed heating system employs a conventional SAW microfluidic system composed of IDTs patterned on a piezoelectric substrate (LiNbO₃). A bimetallic Cr/Au layer with a thickness of 300 Å/1000 Å was deposited onto a 128° y-cut LiNbO₃ substrate (MTI Korea) via e-beam evaporation to build IDTs. In order to generate MHz-order sinusoidal signals, a radio frequency (RF) signal generator (N5181A, Agilent Technologies) was utilized. In addition, a power amplifier (LZY-22+, Mini-Circuits) was used to increase the amplitude of the sinusoidal signals. The electrical power for the power amplifier was supplied at 24V by a DC power supply (E3634A, Agilent Technologies). The output signal of the power amplifier was controlled by modulating the input signal produced by the RF signal generator. A special type of filter paper (ashless filter paper, Grade 41, Whatman), which is nearly composed of pure cellulose fibers, was used to absorb leaky SAWs. The temperature of the heating system was measured and monitored by an infrared camera (A325sc, FLIR Systems, OR, USA). As for the glucose detection experiments, D-glucose powder (Dextrose, anhydrous, 98.0%, Samchun Pure Chemical Co., Ltd.) and Benedict’s reagent solution (Samchun Pure Chemical Co., Ltd.) were used.

5. Conclusions

In a variety of engineering applications, viscoelastic behaviors leading to energy dissipation in the form of heat have been regarded as an unintentional side effect. In this study, however, we harnessed the viscoelastic properties of filter paper to generate heat, and consequently make use of the heat to accelerate and promote chemical reactions involved with heating in paper microfluidics for POC diagnosis. We confirmed the viscoelastic behaviors of filter paper under SAWs produced by a split IDT and identified the most efficient frequencies for acoustothermal heating with a SIDT whose frequency range is from 5 to 55 MHz.

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