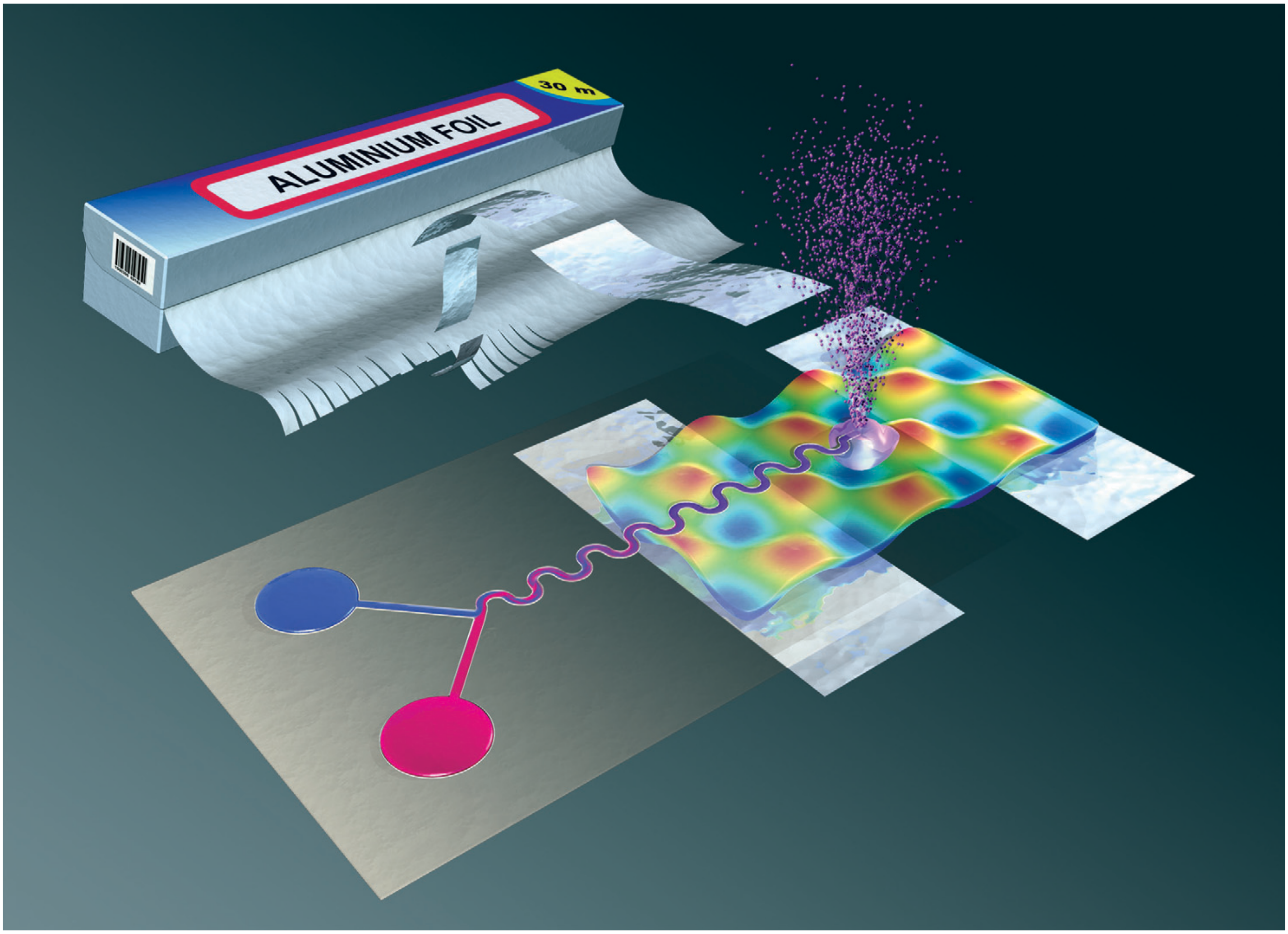

Featuring work from the Micro/Nanophysics Research Laboratory of Professors Leslie Yeo and James Friend, RMIT University, Australia.

Title: Simple, low cost MHz-order acoustomicrofluidics using aluminium foil electrodes

Aluminium foil strips circumvent the need for elaborate and costly photolithographic electrode fabrication for simple, low-cost chip-scale acoustofluidics.

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Simple, low cost MHz-order acoustomicrofluidics using aluminium foil electrodes

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It is now possible to circumvent costly and complex cleanroom fabrication procedures to produce MHz-order acoustically-driven microfluidic platforms through the use of electrode strips cut simply from kitchen aluminium foil and pressed against piezoelectric substrates. Cleanroom deposition, lithographic patterning, and etching are entirely avoided in favor of this cut-and-place technique, which enables the generation of acoustic Lamb waves of sufficient amplitude to demonstrate rapid and efficient microfluidic transport and manipulation, microcentrifugation, and even nebulization of both sessile drops and paper-based substrates. Elimination of microfabrication processes typical of acoustic microfluidics brings us a significant step closer towards commercially-viable consumer diagnostic devices, especially for use in the developing world.

The prohibitive cost and complexity of microfluidic technology are common factors explaining why only a very small fraction of microfluidic devices have so far successfully navigated the arduous commercial translation path to reach the vast point-of-care diagnostics market. These factors are far more critical in the developing world where medical needs are at their greatest and extremely low costs and simplicity of operation are of utmost importance.[1] Of late, considerable effort has been made to simplify and reduce the cost of microfluidic devices for the technology to be useful to both the developing world and the consumer market of the developed world. Some of the most well-known examples of simple, inexpensive microfluidic platforms are paper-based[2,3] or even thread-based;[4] 'print-n-shrink'[5] and lab-on-a-foil[6,7] technologies are also recent, innovative processes that promise to deliver inexpensive microfluidic devices.[8]

Fortunately, after fabrication, the transmission of acoustics excitation into a microfluidics device can be simply enabled with the use of a fluid couplant.[9] Nevertheless, the cost and effort involved in fabricating the piezoelectric ultrasonic resonator—especially the electrode structure[10]—remain significant limitations. Whether fabricated as complex, fingerlike interdigitated (IDT) electrodes, as in surface acoustic wave (SAW) devices,[11] or with simple, complete face electrodes typical of thickness-mode ceramic piezoelectric resonators, the electrodes are nearly always directly deposited and patterned on the piezoelectric material because of justifiable concerns over the generation of charge concentration and hysteresis effects from flaws in the electrode–piezoelectric interface.[12] We have learned in this study that such concerns are not always warranted, that loose electrodes of a soft material such as aluminium against a polished, single-crystal piezoelectric medium like lithium niobate can form a very effective resonator, powerful enough to deliver similar capabilities as the SAW-based microfluidics devices that have received considerable attention to date.[11]

In this work, we demonstrate the use of aluminium foil electrodes placed in contact with a lithium niobate substrate (LN, 127.86° *Y*-rotated, *X*-propagating; Roditi Ltd., London, UK) (Fig. 1(a)) to circumvent the cleanroom fabrication process and its concomitant costs required to pattern metal electrodes on piezoelectric substrates for high frequency ultrasonic microfluidics, which has been a subject of recent widespread interest,[13,10,14,11] both in terms of droplet[15] and microchannel[16] platforms for applications across drug delivery,[17] biosensing,[18] cell sorting,[19,20] and disease diagnostics.[21] The procedure is straightforward: we simply cut ~50 μm thick aluminium foil (Goliath™, ALDI Stores, Minchinbury, NSW, Australia) purchased at a grocery with a pair of scissors and press it in contact with the LN chip that is pre-cut to a desired size using a glass cutter and a metal ruler as a scribe-line breaker. Here, we employ contact probes fixed in position using magnetic rings to connect the aluminium foil to the power supply. In a manner analogous to a recent low-cost electrokinetically-driven paper-based microfluidic platform,[3] we show in the present work, amongst the other microfluidic manipulations that are possible, that we can replicate—albeit with greater simplicity and lower costs—the rapid and

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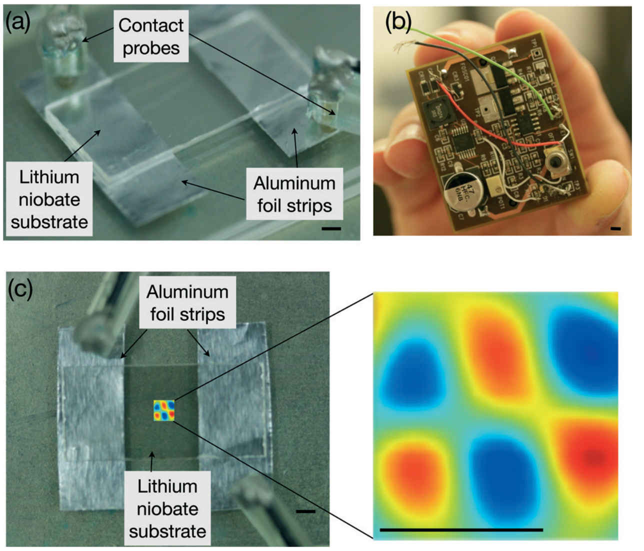

Fig. 1 (a) The device simply comprises a glass scribe-cut lithium niobate piezoelectric substrate chip placed atop two strips of kitchen aluminium foil cut with a pair of scissors. (b) Portable palmtop driver circuit used for the SAW experiments that runs on a pair of small CR123 camera batteries.[17,23] (c) Top-down image of the device overlaid with a LDV scan of the surface displacement; the inset shows a magnification of the scan verifying the existence of a two-dimensional Lamb wave pattern. Scale bars ~1 mm.

efficient microfluidic transport in paper-based substrates using SAW,[22] whose considerable advantages of enabling uniform flow and highly reproducible mixing over passive capillary-driven paper systems are unfortunately complicated by the cost of fabricating the SAW devices themselves.

Of the various processes enabled by MHz-order acoustic microfluidics,[23] the nebulization process necessary to transport fluid through the paper device[22] as well as for pulmonary drug delivery,[17] protein extraction[24] and mass spectrometry[25,26] requires the highest power given its need to overcome the large capillary stresses associated with the fluid meniscus in order to deform and eventually break up the fluid interface.[27] Thus while SAW nebulization offers a number of advantages over other methods, key among them being the possibility for low power operation compatible with battery-powered (Fig. 1(b)) handheld devices,[17] it unfortunately involves fabrication methods that remain complex for even the simplest of electrode structures, prohibitively so for low-cost applications.

A partial solution to the problem is the use of Lamb waves on a glass substrate on millimeter to centimeter-order length scales with a hard lead zirconate titanate piezoelectric block resonator glued to the glass;[28] though the construction is simple, the device is large and the performance is insufficient for handheld operation. In fact, Lamb waves were explored long ago for fluid transport on small scales[29] but, even with appropriate device dimensions, the performance was far from adequate, especially if portable battery operation is desired, and the fabrication process far from simple. The latter point is true of all microscale Lamb wave devices we are aware of:[30,31,29] they utilize the same IDTs as that used for generating the SAW, and therefore offer no particular fabrication advantages over the SAW devices.

Here, Lamb waves are generated from a much simpler design suitable for fabrication in a typical laboratory without necessitating the use of a cleanroom and yet offering performance sufficient for point-of-care diagnostic applications while being run from a palmtop battery-powered driver circuit. Standard aluminium foil was cut into rectangular strips ~3 × 10 mm using a pair of scissors and subsequently gently clamped into contact with the LN substrate (Fig. 1(a)). A MHz-order alternating current was then applied to the foil, giving rise to Lamb wave resonances throughout the LN substrate,[32] as determined by the laser Doppler vibrometer (LDV, UHF-120, Polytec GmbH, Waldbronn, Germany) scan shown in the inset of Fig. 1(c); the scan was performed on both sides of the substrate to confirm the *absence* of other forms of wave excitation. The Lamb wave resonant frequencies increase in proportion to a decrease in the substrate thickness. At 500 μm, the fundamental antisymmetric mode appeared at 3.5 MHz. The same fundamental Lamb wave mode doubled to 7 MHz when the substrate was lapped to 250 μm thickness. Many harmonics of this mode were found to be present at equally spaced frequencies beyond this mode, though the fundamental mode (unless otherwise indicated) appeared to offer the most efficient microfluidic actuation.

Because the SAW is locally confined to only a few wavelengths below the surface of a substrate—it is perceived to be more efficient than Lamb waves which propagate throughout the bulk of the substrate and can lose energy due to mounting. Remarkably however, despite the crude nature of the aluminium foil, the power required even for nebulization is sufficiently low such that it can be supplied by the portable driver circuit—a key design requirement. Moreover, the aluminium foil electrodes are placed on the *bottom* of the LN chip and therefore leaves the top surface of the LN free for the fluid operations in addition to whatever else is needed for the application without concern for the electrodes, unlike the difficulties one must deal with in using the SAW device where the fluid actuation is isolated to the IDT aperture—or less in the case of focusing IDTs.

More specifically, nebulization from a drop placed on the reverse face of the substrate to which the aluminium foil is attached is shown in Fig. 2 at power levels from as low as approximately 330 mW—two orders of magnitude smaller than those used in conventional ultrasonic nebulizers, slightly lower than those used with the SAW, and easily supplied by our portable battery-operated driver circuit (Fig. 1(b)). When the device is placed in contact with the outlet of the virtual fluidic channel, patterned on a paper-based substrate using a similar method to the FLASH (Fast Lithographic Activation of Sheets) protocol,[2] we show that we are able to replicate our previous results for driving rapid and uniform fluid transport through the paper with the SAW device without the disadvantages of backflow and variability associated with passive capillary-driven flow (Fig. 3(a)).[22] When two different fluids

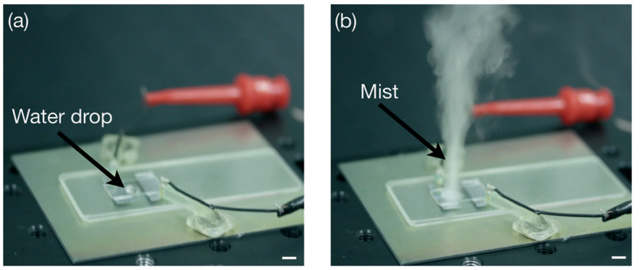

Fig. 2 (a) A 5 μL sessile water drop pipetted onto the LN substrate is (b) completely nebulized within 2 s when Lamb waves are excited on the substrate *via* a 500 mW, 3.5 MHz AC electrical signal to the aluminium foil strip placed underneath the substrate. The nebulized aerosol mist has a Sauter mean diameter of 3.5 μm. Scale bars ~5 mm.

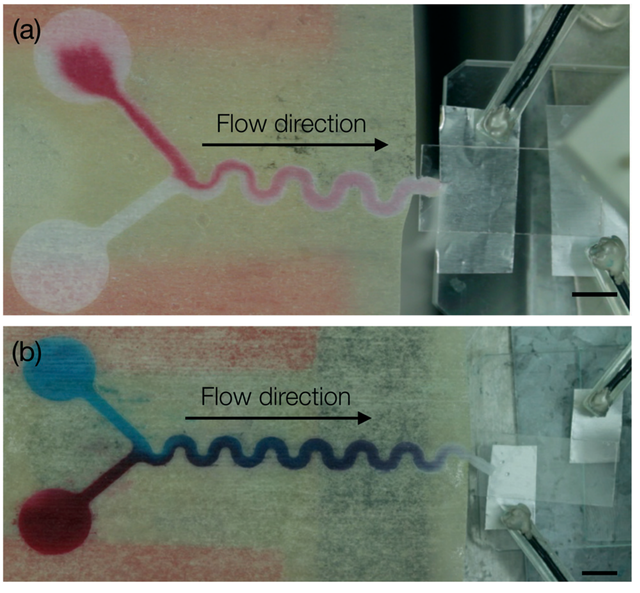

Fig. 3 (a) Fluid nebulization at the outlet edge of a Y-channel patterned onto paper in contact with the LN substrate, on which Lamb waves are excited, is observed to drive rapid flow through the paper without backflow into the other arm of the inlet channel, similar to but much more conveniently than with the SAW device.[22] (b) Two differently dyed fluids placed in the inlet reservoirs on each Y-channel arm are observed to be rapidly and uniformly mixed as they are transported through the serpentine sections of the channel due to nebulization at the outlet. The applied frequency and power to the device are 3.5 MHz and 0.95 W, respectively. Scale bar ~5 mm.

are placed separately in the inlet channels, fast and uniform mixing through the paper channel is achieved with the simple low-cost device (Fig. 3(b)), again overcoming limitations of poor reproduceability and nonuniformity associated with mixing in pure capillary-driven paper devices.[22]

In addition to fluid transport through paper-based substrates, we also briefly show that the simple device is able to replicate the range of microfluidic functionality of the SAW with comparable efficiencies. By breaking the symmetry of the Lamb wave, which can be achieved by either using an asymmetric chip geometry (for example, a triangular device instead of one that is rectangular), using asymmetric electrodes, or slanting one of the aluminium foil electrodes, colloidal particles suspended in the drop can be rapidly concentrated in a manner akin to that shown in SAW microcentrifugation[33,34] (Fig. 4). Similarly, rapid mixing within a sessile drop due to chaotic acoustic streaming[35] and capillary wave vibration can also be induced, as shown in Fig. 5.

Together with the powerful potential of high frequency (MHz-order) acoustofluidic actuation and the ability to use a portable palmtop driver circuit, we believe that the replacement of the costly, complex and cumbersome fabrication procedures required for the patterning of IDTs in SAW and traditional Lamb wave devices with the simple use of strips of aluminium foil is a significant step that addresses issues surrounding the costs and reliability of active microfluidic actuation platforms, especially for use in the developing world and consumer devices in the developed world.

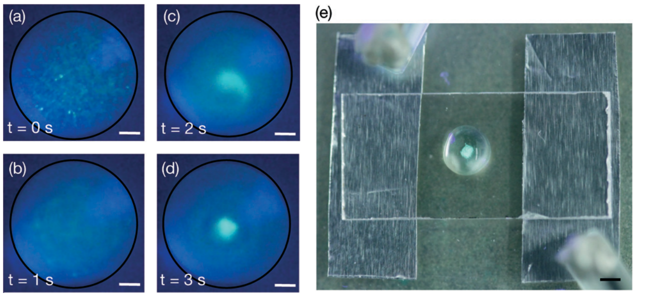

Fig. 4 (a–d) Time sequence of images showing an initial 3 μL sessile drop comprising a suspension of 4.5 μm fluorescent polystyrene microparticles (Polysciences Inc., Warrington, PA) at t = 0 being rapidly concentrated to its centre within 2 s due to the fast azimuthal microcentrifugation flow that arises under Lamb wave excitation of the underlying substrate at a frequency of 17.5 MHz with an input power of 90 mW. Circles are drawn around the edges of the drop to clarify their location in the images and the scale bar represents a length of ~300 μm. (e) The particles remain aggregated even after removal of the Lamb wave vibration; scale bar ~1 mm.

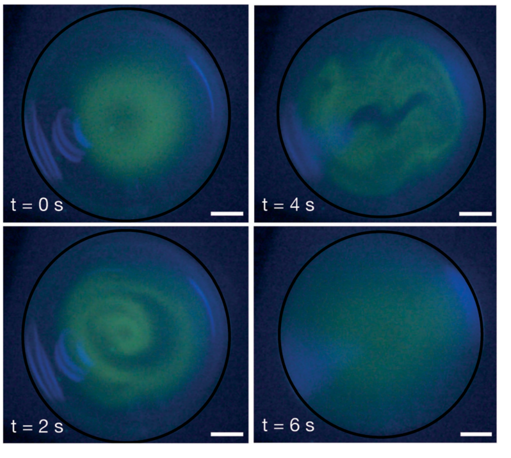

Fig. 5 Sequence of images in time showing rapid mixing of a 1 μL drop of fluorescent dye (fluorescein, Sigma-Aldrich Pty. Ltd., Castle Hill, NSW, Australia) added to a 10 μL water drop driven by Lamb wave excitation at 17.5 MHz and 0.11 W. Circles are drawn around the edges of the drops to clarify their position in the images and the scale bars are ~300 μm.

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