On-chip surface acoustic wave driven microfluidic motors

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ABSTRACT

We report on the design of two different surface acoustic wave (SAW) driven rotary motors. Both designs use 20–30 MHz transducers patterned onto Lithium Niobate (LN), geometrically tailored to generate Rayleigh waves that are incident on opposing sides of each rotor. The first design exploits the efficient coupling between SAWs and fluids by use of a fluid coupling layer between the rotor and substrate, leading to rotations of a 5 mm disc shaped rotor over 2,500 rpm with a start-up torque of 60 nN m. The second design exploits a dry friction contact between the surface and rotors for further miniaturisation. In the latter design 1 mm steel rotors are driven up to 6,000 rpm with no external preload required.

Keywords: Surface acoustic waves, motors, friction, microfluidics, MEMS, Lab-on-a-Chip

1. INTRODUCTION

Due to the inadequacy of current miniaturised motor technology, small-scale motors are increasingly becoming more important for the development of portable devices for a large number of applications.[1] Surgical tools, actuators for biological and chemical analysis, and portable diagnostic systems are a few of the areas in which microscale actuation is necessary. Many current micro-motor designs require complex and precise designs, and additionally are inadequate in either rotary speed or torque for most lab-on-a-chip (LOC) applications. *Surface acoustic waves* (SAW) have been shown to be an excellent means for driving high-speed fluid actuation, and have demonstrated a variety of functions including micromixing and centrifugation.[2]

There has been some attempts to exploit SAW to drive rotational motors in the past, however these have typically been overly complex and suffering from poor performance.[3,4] We now report on the design of two SAW driven rotary micromotors that can generate high-speed rotation that can be easily incorporated into microfluidics with modest power requirements suitable for a truly portable device. Both these designs are simple enough to allow easily for further miniaturisation. The first device consists of a circular 5 mm disc rotor coupled with a fluid drop contained in a hydrophobic well placed asymmetrically in the propagation pathway of two counter-propagating SAWs.[5] We generate a rotating flow throughout a fluid drop via acoustic irradiation of two geometrically tailored SAWs to drive the rotary micromotor. The large mass flow that may be induced by acoustic irradiation and the large amount of power that may be transmitted using SAW, make it possible to drive the rotation of a thin disc at relatively high rotation speeds. Further miniaturisation of the rotors led to unstable rotations as the rotors began to precess about the fluid and spin out from the apex of the fluid. The second motor design exploits a frictional contact mechanism to drive smaller 1 mm diameter rotors at even higher rotary speeds. Both designs require no external pre-load.

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2. METHODS

A typical SAW device used to drive the fluid coupled motor consisted of a pair of interdigital transducers (IDT) patterned onto a piezoelectric (LN) substrate, as shown in Fig. 1. SAW devices were produced using standard microfabrication techniques. The metal laters consisted of 5 nm of chromium followed by 300 nm of gold. The IDTs, which consisted of 20 straight finger pairs with an aperture of approximately 10 mm, were found to exhibit a resonant frequency of 19.68 MHz using an impedance analyzer (Agilent 4294A, Santa Clara CA, USA). Alternate halves of each propagating waves were blocked by use of silicone-gel, to create asymmetrical flow in the fluid coupling layer, and therefore disc rotor. Waves formed out of the rear of the IDTs were also blocked with silicone gel to restrict reflections interfering with the waveform. With the IDT and a small circular region in the center of the substrate masked with dicing tape, Teflon® AF (E. I. du Pont de Nemours and Company, Wilmington DE, USA) was spun and crystallised on the surface at an approximate thickness of 100 nm to form a hydrophilic region to confine the fluid layer during operation of the motor. The 5 mm rotors in the fluid coupled motor were punched from ~ 100 μm thick patterned mylar.

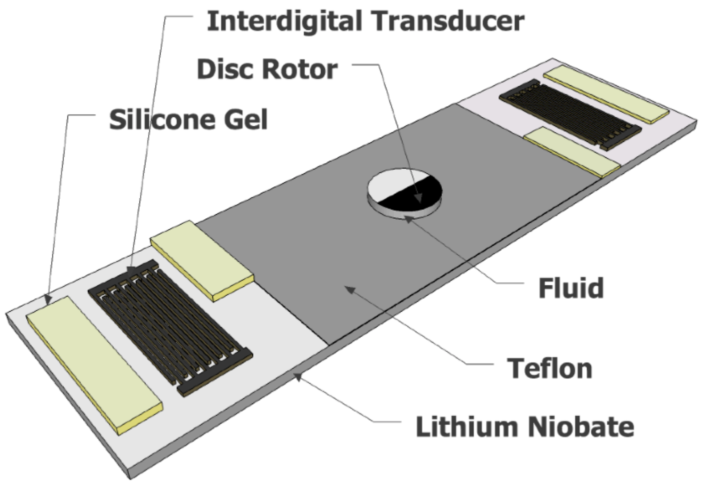

Figure 1. Schematic of the rotational fluid-coupled micromotor with 5 mm rotor (not to scale).

A typical SAW device used to actuate the frictional motor consisted of focussing type[2] single phase unidirectional transducers (SPUDT) to focus the wave precisely on alternate sides of a miniaturised 1 mm diameter steel rotor. The SPUDTs were designed with a 1 mm offset in the y-direction to promote asymmetry of the x-propagating wave and in turn cause the rotors to rotate. The schematic of this motor type is seen in Fig. 2. The substrate was prepared in the same method as the former motor, however with a nominal resonance frequency of 30 MHz. The rotors were housed in silicon etched with a $\sim 80 - 100$ μm deep chamber to hold them in place, with a 40 μm diameter central pin on which to place the rotor (Fig. 2). The figure shows an open configuration for viewing of the rotor positioning, however the rotor was enclosed in silicon for operation. The etched silicon was bonded to the LN with UV activated adhesive, with glue thicknesses on the order of a micron. The 1 mm rotors were fabricated from 55 μm thick steel sheets (Fig. 3).

Motor operations were captured via a high-speed video camera up to $\sim$ 6000 fps (Mikroton MC1310, Unterschleissheim, Germany), and rotational speeds were calculated from the rotor angles in the videos using the computer software ImageJ (National Institute of Health, Bethesda, USA).

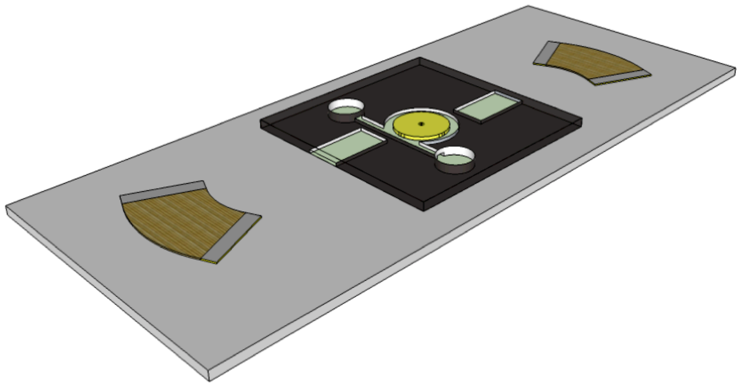

Figure 2. Schematic of the rotational dry-friction micromotor with 1 mm diameter rotors (not to scale).

Figure 3. 1 mm diameter, 55 μm thick steel rotor used with the friction driven SAW motor. Notches were cut into each side to allow for visualisation of the high speed rotations.

Rotary motors actuated by piezoelectrics are known to respond as a first order dynamical system which may be modelled by an exponential fit.[6,7] Each spin-up curve shown in the following section was fit to the following exponential function by a least squares fit,

$$\omega(t) = \omega_{ss}(1 - e^{-\frac{t}{\tau}}), \tag{1}$$

where $\omega(t)$ is the unloaded rotation speed, ω_{ss} is its steady-state speed, t is the time and τ is the characteristic time constant. From these fits we are able to completely define the motors operation for comparison and analysis, and are also able to calculate start up torques on these rotors.

3. RESULTS, DISCUSSION AND CONCLUSIONS

The rotational speeds of the disc rotor were found to increase linearly with an increase in the average surface displacement up to a maximum of up to 2,500 rpm. Preliminary findings have shown that reducing the disc rotor size increases the maximum rotational velocities achievable however this also led to large instabilities in the discs rotations as they would tend to precess and spin out from the fluid-coupling layers apex.

The rotational velocities achieved after applying the SAW can be seen in Fig. 4. Over the range of surface displacements, the electrical input power applied to each IDT was of the order $0.1 - 1$ W, although the actual power into the fluid is considerably less. The average surface amplitudes of the propagating SAW were measured with a laser doppler vibrometer (LDV), and the rotational spin-up curves are compared against these values in Fig. 4. Increasing the applied power increases the SAW surface amplitudes. As we increase the SAW amplitude to over $\sim$ 3nm the disc rotation becomes unstable and begins to precess. Further increase in surface displacements leads to highly unstable operation with an associated drop in performance and some droplet translation or fluid jetting.

Figure. 5 shows the maximum torque on the rotors against surface displacements. There is a significant increase in torque values as the surface amplitudes are increased, to a maximum torque over 60 nN-m at a SAW amplitude of $\sim$ 2 nm. Beyond this the rotations become very unstable and the start-up torque drops dramatically.

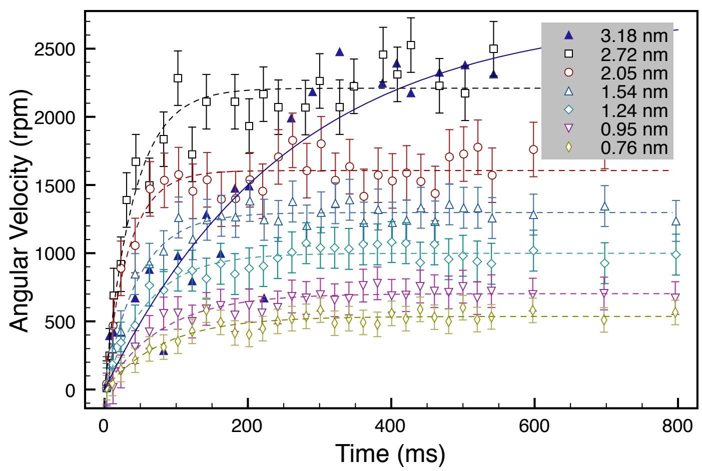

Figure 4. Spin-up curves for the fluid-coupled 5 mm diameter rotor for increasing average SAW amplitudes. The start-up time is seen to increase dramatically above a displacement of $\sim$ 3 nm, as the rotor becomes unstable and begins to precess. Further increase of SAW amplitude leads to a dramatic decrease in stability and performance.

Further reductions in rotor size became problematic as the rotors, although obtaining higher rotary speeds, would typically spin-out from the fluid apex and become stuck, owing to the problems in precisely placing smaller rotors on fluid droplets using this configuration. Investigations have begun using precisely focussed SAW transducers, to drive 1 mm rotors without the need for fluid layers.

Figure 6 shows the spin up curve of this type of motor. There is no need for an externally applied pre-load, as the small scale adhesive forces are significant enough to provide enough pre-load for operation. With a SAW transverse vibration velocity of approximately 1 m/s applied on either side of the rotor, the motor is found to reach a steady-state velocity of $\sim$ 6000 rpm in approximately 20 ms. The torque associated with this operation is on the order of 4 nN-m, comparable to motors of similar size and operation. Further studies are being carried out to investigate rotors with reduced mass to test for further increased rotary speeds.

Rotations were found to occur *towards* the direction of SAW propagation in the second type of motor, opposite to the direction of rotations for the fluid-coupled motor. There are two possible mechanisms of rotor propulsion for this setup, either frictional contact or acoustic levitation. If acoustic levitation were causing rotations, the rotors would be expected to rotate in the same direction as the SAW propagation, and at higher rotation speeds

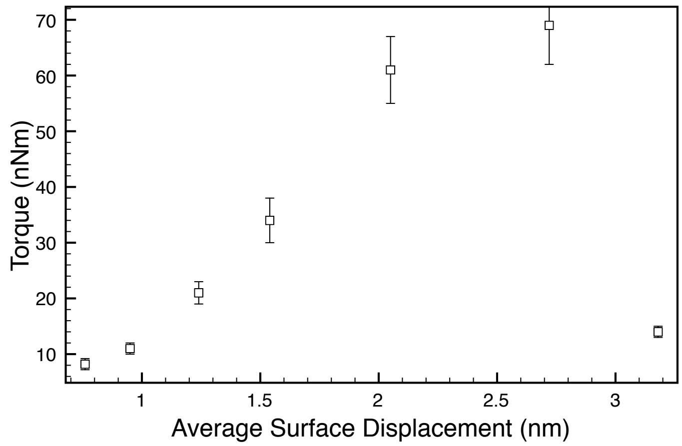

Figure 5. Start-up torques for the 5 mm diameter fluid-coupled rotor for increasing average SAW amplitudes. The torque is seen to increase quite linearly with SAW amplitude until the rotor becomes unstable at a SAW displacement of ~ 3 nm, where the torque drops dramatically.

to what is observed.[8,9] The rotor direction therefore indicates the rotor is in frictional contact with the LN substrate. The retrograde motion of the substrate as the Rayleigh SAW propagates along it would cause a surface in frictional contact with it to move in a direction opposing the SAW propagation.

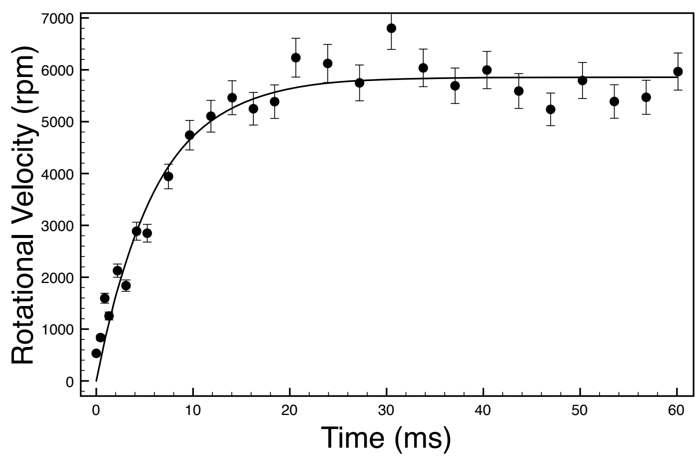

Figure 6. Spin-up curves for friction driven 1 mm diameter rotors.

4. CONCLUSIONS

We have demonstrated a SAW fluid-coupled motor able to drive 5 mm rotors to rotary speeds of over 2500 rpm with maximum torques over 60 nN-m. We also demonstrated a SAW frictional contact motor able to drive 1 mm rotors to over 6000 rpm with torques over 4 nN-m Providing a simple, miniaturised method for driving efficient and fast rotary motion, the main attraction of the technique is its ability to be incorporated into lab-on-a-chip devices.

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