Published in final edited form as:

J Microelectromech Syst. 2018 June ; 27(3): 547–554. doi:10.1109/JMEMS.2018.2823980.

Miniature bulk PZT traveling wave ultrasonic motors for low-speed high-torque rotary actuation

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Abstract

Traveling wave ultrasonic micromotors fabricated from a single layer of homogeneous bulk piezoelectric lead zirconate titanate (PZT) are described. The miniature motors are capable of bi-directional rotary motion with controllable speeds. By taking advantage of transverse interdigitated electrodes to excite traveling waves in a patterned bulk PZT substrate, the monolithic micromotor stators are patterned using a simple and low cost fabrication technique based on micropowder blasting. Performance of the ultrasonic micromotors is explored using devices with integrated glass rotors, using defined preload forces applied between the microfabricated stator and rotor elements. For the case of a 4.12 mm diameter PZT stator, a maximum speed of 30 rpm and stall torque of 501 mN · mm are achieved when applying a 323 mN preload force to the rotor.

Index Terms

piezoelectric; micromotor

I. INTRODUCTION

Rotary microactuators have long been an important focus of microsystems research, with the first micromotors using electrostatic stepping actuators fabricated by polysilicon surface micromachining reported in 1989 [1]–[3]. A range of electrostatic micromotor designs were explored shortly thereafter, including oscillatory impact micromotors [4], wobble micromotors [5], [6], and two-axis direct-drive motors using polysilicon friction bearings [7]. More recently, a variety of microfabricated motors incorporating magneto-elastic and electromagnetic transduction mechanisms have also been demonstrated [8], [9]. While capable of operating at high speeds, these micromotors generally suffer from low output torque, limiting their utility for practical applications that demand high torque and controllable speeds, such as autofocus lenses for cell phone cameras, catheter-based imaging systems, and actuators and end-effectors for miniature robotic platforms.

Ultrasonic micromotors offer a potential solution to this limitation. Ultrasonic motors employ piezoelectric transduction to induce vibrations within a fixed stator, leading to standing or traveling waves within the stator element that transfer mechanical energy into a frictionally-coupled rotor. Traveling wave ultrasonic motors are of particular interest due to their ability to provide controllable rotation with submicron positioning in both the forward and reverse directions, unlike standing wave designs in which the direction of motor rotation

is fixed. Rotor speed can be controlled by adjusting the traveling wave amplitude, with low speed operation achieved without the need for reducing gears or other complex mechanical components. Ultrasonic motors have several additional advantages over their electromagnetic and electrostatic counterparts, including immunity from electromagnetic interference and the ability to maintain a stable output position without the need for external power [10].

At the macro-scale, ultrasonic motors have been widely studied since their invention in the 1930s [11]–[16], and a variety of design have been investigated at the millimeter scale using 3-D tubular traveling wave motor designs [17]–[20]. However, these tubular designs require assembly of discrete components and are not amenable to batch fabrication. In contrast, a planar traveling wave ultrasonic motor concept described by Sashida in 1983 [21] was commercialized for camera autofocus mechanisms and wrist watches [22]–[23]. In this design, electrodes are configured on a piezoelectric bimorph disk or annulus to enable the generation of an elastic wave that travels circumferentially within the stator, resulting in rotation of a rotor placed in frictional contact with the stator surface. The first efforts toward the application of microfabrication techniques to reduce the size scale of the Sashida design using thin film [24] or bulk [25] PZT were undertaken by Flynn et al. in the 1990s. While rotary motion was achieved in these millimeter-scale devices, bi-directional control of rotor motion remained elusive due to fabrication challenges limiting the fidelity of traveling waves within the stators. More recently, a millimeter-scale traveling wave motor utilizing thin film PZT on silicon-on-insulator wafers was reported to successfully achieve bi-directional rotation [26], [27]. While high speeds up to 2000 rpm were achieved for a 3 mm diameter rotor, low stall torque in the nN-mm range was observed. Furthermore, the devices required a relatively complex fabrication process involving six photolithography steps together with wafer-scale sol-gel processing of the thin film PZT required for piezoelectric actuation of the stator.

In this work, we present a unique millimeter-scale rotary traveling wave micromotor design that employs a stator fabricated from a homogeneous sheet of bulk PZT, using a photolithographic micropowder blasting process that is compatible with batch fabrication methods for high throughput manufacture. Because the micromotor stators are fabricated using a single PZT substrate which serves as both active and elastic layers for the formation of bending-mode traveling waves [28], the resulting stators do not suffer from temperature sensitivity or fabrication-induced residual stresses common in bimorph actuators. The use of photolithographic patterning ensures accurate alignment of all electromechanical structures, reducing modal asperities that can degrade the performance of ultrasonic micromotors that rely on assembly of multiple components for operation. These features are enabled by the use of transverse interdigitated electrodes that support an actuation scheme in which the piezoelectric stator is actuated in its thickness, rather than longitudinal, mode. Detailed characterization of fabricated 4 mm diameter stators is presented, together with bi-directional rotor motion of a microfabricated glass rotor, with stable speeds ranging from 730 rpm demonstrated, and stall torque as high as 501 mN-mm achieved.

II. MICROMOTOR DESIGN

Ultrasonic motors operate through the generation of elastic waves through the converse piezoelectric effect, wherein strain is generated in response to an applied electric field within a piezoelectric stator element. In traveling wave ultrasonic motors, two independent standing waves are generated by applying periodic inputs shifted by a quarter wavelength in both time and space [21]. The superimposed sinusoidal standing waves, each with the form of $\sin(n\theta)\sin(\omega t)$ where n is the number of circumferential nodes, θ is the angular polar coordinate, ω is the actuation frequency, and t is time, lead to the formation of a traveling wave, as can be seen by the following trigonometric identity,

$$\sin(n\theta)\sin(\omega t) + \cos(n\theta)\cos(\omega t) = \cos(n\theta - \omega t) \quad (1)$$

Under the influence of the resulting traveling wave, particles on the stator surface follow elliptical trajectories with retrograde motion. Momentum is then transferred from the stator to a rotor placed in frictional contact with the stator surface, as shown in Figure 1, using a defined preload force between the stator and rotor to control frictional coupling. Due to the retrograde circumferential motion of the stator surface at the peak of the traveling wave, the rotor element rotates in the opposite direction of the stator traveling wave itself. To ensure mechanical stability of the rotor during actuation while minimizing the required signal frequency, the traveling wave is typically generated in a B_{03} mode with zero radial nodes and three circumferential nodes ($n = 3$).

Stators in conventional macro-scale traveling wave ultrasonic motors are manufactured with a piezoelectric layer bonded to an elastic layer. This bimorph structure serves to offset the neutral axis of the composite structure, allowing bending-mode vibrations to be excited by the piezoelectric material. In some cases, the elastic layer is also used to introduce raised features that serve to amplify motion of the stator surface during travelling wave propagation. The bimorph design allows circumferential strain in the piezoelectric ring to produce bending motion, and thus standing waves, within the stator. Using patterned electrodes on the top surface of the piezoelectric layer and a continuous ground electrode on the bottom surface, circumferential strain (S_1) is generated due to the applied electric field (E_3) across the thickness of the piezoelectric film through the transverse coupling coefficient (d_{31}) following a simplified constitutive relationship given by $S_1 = d_{31}E_3$. This conventional approach is depicted in Figure 2a, with three groups of four parallel plate electrodes used to generate the desired B_{03} traveling wave from $\pm\sin(\omega t)$ and $\pm\cos(\omega t)$ voltage pairs to establish the constituent standing waves.

For the development of miniature traveling wave ultrasonic motors, a central disadvantage of transverse-mode piezoelectric actuation is the need for electrodes on both the upper and lower surfaces of the piezoelectric layer to form an electric field through the thickness of the piezoelectric, together with the need for an elastic substrate bonded to the piezoelectric layer to offset the stator's neutral axis. While microfabrication of composite stator structures has been demonstrated for ultrasonic motors [24]–[27], the manufacturing processes rely on complex microfabrication methods or require assembly of discreet miniature components.

To overcome these limitations, here we report a new fabrication process that allows integrated stators to be directly patterned from a single sheet of bulk ferroelectric material, greatly simplifying the microfabrication process while simultaneously improving stator performance. The process is demonstrated in this work using commercially-available 127 μm thick PZT sheets, but in principle the fabrication process is compatible with any ferroelectric substrate. Bending mode actuation of the PZT is achieved by taking advantage of transverse interdigitated electrode actuation [28], which utilizes a pair of interdigitated electrodes patterned on a single side of a homogeneous piezoelectric substrate. When a voltage is applied between the electrodes, the resulting electric field follows isoclines that lie primarily within the plane of the substrate, rather than transverse to the substrate as in the case of conventional stator designs utilizing parallel plate electrodes. By tuning the distance between adjacent electrode pairs, the penetration depth of the electric field into the piezoelectric substrate may be adjusted, enabling the formation of an active region of the stator where strain is generated through the converse piezoelectric effect and a passive region where negligible strain is produced. In this way the passive region acts as the elastic portion of a bimorph, allowing bending strain to be generated in the device.

A schematic of the transverse interdigitated electrode configuration is depicted in Figure 2b. Because the electric fields within the piezoelectric stator are proportional to the voltage difference between adjacent electrodes, while the signals are themselves out of phase in time and space by 90° , this drive method is termed differential quadrature actuation. In addition to enabling the generation of bending strains in a single layer of PZT, a further benefit of differential quadrature actuation is that the effective applied voltage is enhanced by a factor of $\sqrt{2}$ over parallel plate actuation due to the differential input signals, as shown in Figure 2b. Furthermore, by poling the ferroelectric material using the same actuation electrodes to align the piezoelectric dipoles during device fabrication, the resulting actuation strain is dependent on the longitudinal piezoelectric coupling coefficient (d_{33}) rather than the transverse coefficient (d_{31}). Because d_{33} is typically greater than d_{31} for piezoelectric materials, stator performance can be further enhanced through the use of differential quadrature actuation.

III. Stator and Rotor Fabrication

A fabricated PZT stator for a traveling wave ultrasonic motor is presented in Figure 3. The stator consists of an annular ring attached to the surrounding PZT substrate by twelve tethers, which also serve to carry electrical drive signals from external bond pads to the interdigitated electrodes on the ring.

The PZT stator fabrication process is summarized in Figure 4. The stators were fabricated from 7.24 cm square and 127 μm thick PZT sheets (type 5A, PSI5A4E, Piezo Systems, Inc.) using a lithographic process combining wet etching for electrode patterning with micropowder blasting for selective PZT etching. Each PZT sheet was purchased pre-poled through its thickness axis, with a 2 μm thick nickel metallization layer on both surfaces. The nickel film on the upper surface was removed by wet etching (Nickel Etchant TFB, Transene Company, Inc.), and the PZT sheet was temporarily bonded to a 4 inch silicon wafer using a wax sheet (4 inch mounting wax discs, Allied High Tech Products, Inc.) to provide a mechanical support for further process steps. Aluminum was evaporated onto the PZT to

obtain a 500 nm thick film. Transverse interdigitated electrodes were patterned in the aluminum film by spin coating a 2- μm -thick layer of positive resist (S1813, Microchem) as a mask and aluminum was etched using a commercial etchant (Aluminum Etchant Type A, Transene Company, Inc.). A 100 μm thick glass coverslip was used as a hard mask for these stators. Using a 50 μm thick dry-film photoresist (RapidMASK, Ikonics Corporation) layer to mask the coverslip, micropowder blasting was performed using a benchtop microabrasive blasting workstation (AccuFlo MB1000 MicroBlaster, Comco Inc.) with 25 μm alumina particles to pattern the glass hard mask. This mask was then optically aligned and temporarily bonded to the PZT layer using a wax sheet, and micropowder blasting was performed to pattern the PZT. For both micropowder blasting steps, the abrasive nozzle was held at a constant 6 cm distance from the PZT substrate during the etch using a nozzle pressure of 60 psi and an etch time of 80 s. For the devices described in this paper, stators with 4120 μm outer diameter and 2080 μm inner diameter annular rings, resulting in 510 μm ring width, and varying flexure dimensions were fabricated using this process.

The micromotor rotors were fabricated from 100 μm thick glass coverslips using micropowder blasting and dry film photolithography following our previous work [28][29], as shown in Figure 5. A 20 μm thick permanent dry film negative resist (DFR 3020, EMS Adhesives) was used to pattern a 1500 μm diameter post in the center of each glass rotor. When seated into the 2080 μm inner opening of the stator, this post served to prevent lateral displacement of the rotor during micromotor operation. An image of a fully integrated stator/rotor pair fabricated using this process is presented in Figure 6.

IV. Motor Characterization

A. Piezoelectric performance after micropowder blasting

Micropowder blasting provides a simple and rapid approach to etching brittle materials such as PZT. When combined with dry film photoresist as a lithographically-defined masking layer, this subtractive patterning technique has been shown to enable fabrication of bulk PZT microstructures with line and space resolution below 100 μm , with etch rates on the order of tens of micrometers per second [29]. While this patterning method has been successfully applied to the fabrication of single-layer bulk PZT microactuators with transverse interdigitated electrodes [28], our initial attempts to pattern ultrasonic micromotors by micropowder blasting resulted in irreproducible results and low overall transduction performance, with increased degradation of piezoelectric properties as the stator ring width was reduced. To explore the issue, a series of PZT cantilevers with interdigitated electrodes of 50 μm electrode spacing, with the electrodes spaced 50 μm from the edges of PZT were fabricated by micropowder blasting using a dry film photoresist mask, and capacitance between the electrode pairs was measured as a proxy metric for the piezoelectric properties of the devices. The resulting data, presented in Figure 7, shows that capacitance rapidly decays as the beam width drops below 700 μm . We hypothesized that this degradation resulted from slight delamination of the dry film photoresist during powder blasting, allowing alumina particles to become embedded within the outer edges of the device and damaging the PZT surface in these regions. This hypothesis was verified by energy-dispersive x-ray spectroscopy, which revealed the presence of aluminum on the top

surface of fabricated cantilevers near the device edge (data not shown). To resolve this issue, the etching process was modified by first using micropowder blasting to fabricate a glass hard mask which was then bonded to the PZT surface with wax (Figure 4d). While the exposed wax was readily ablated during powder blasting, it served to maintain a tight seal between the glass mask and PZT surface, preventing the intrusion of alumina particles. Using this approach, less than 10% reduction in PZT capacitance was observed for cantilevers as small as 300 μm (Figure 7).

The commercial PZT sheets used in this work were obtained pre-poled along the thickness axis. In order to actuate the stators with transverse interdigitated electrodes, it was necessary to re-pole the PZT after patterning the interdigitated electrodes to align the piezoelectric dipoles between adjacent electrode pairs. Poling was performed by first heating the bulk PZT sheet to a temperature of 360 °C, slightly above the material's Curie temperature of 350 °C, for 10 min to fully depolarize the material before allowing it to cool down to room temperature. After depolarization, the material was re-poled between adjacent pairs of electrodes by applying an electric field of 4 V/ μm at 100°C for 30 min following our previous work [28]. Final poling was performed sequentially for each pair of electrodes to align the dipoles within all 12 stator segments in the same orientation. Effective poling was verified by actuating each electrode pair individually, and measuring the resulting standing wave amplitude, with typical results shown in Figure 8. This figure also presents standing wave amplitudes for the case of poling without the initial de-poling step, emphasizing the importance of an optimized poling process to achieve the desired piezoelectric performance during stator actuation.

B. Stator Characterization

Stators supported by 200 μm wide tethers with lengths ranging from 800-2000 μm were characterized to explore the impact of anchor length on device performance. For each design, B_{03} mode frequencies were measured experimentally using a scanning laser Doppler vibrometer (LDV, Polytec MSA-500), with measured results compared with numerical models. Although the resulting frequencies were found to be somewhat lower than predicted by finite element analysis (Figure 9), both results follow a similar trend with the resonant frequency proportional to the inverse square of the tether length. In these tests, each electrode pair was individually actuated with a sine wave at the corresponding B_{03} mode frequency to generate standing waves. For a given device, the difference in the B_{03} resonant frequencies between all sections of the stator was found to be less than 2%, while the typical maximum variation in the resulting standing wave amplitudes was approximately 20%.

Next, the fabricated devices were used to study traveling wave generation within the stators. A typical sequence of scanning LDV images for a device with 1 mm long tethers and a B_{03} frequency of 54 kHz is shown in Figure 10, with bidirectional rotation of the traveling waves obtained by reversing the order of input voltages. The traveling wave amplitude was measured as a function of actuation voltage up to the previously established initial depolarizing voltage of 80 V, corresponding to a maximum electric field of 1.6 V/ μm across the interdigitated electrode pairs (Figure 11). The stators exhibited a linear response up to an applied voltage of 50 V, corresponding to a traveling wave amplitude of approximately 200

nm. Above this voltage, a highly nonlinear response was observed, with a maximum amplitude of nearly $2\text{ }\mu\text{m}$ achieved as the voltage approached the depolarization limit. This behavior is likely due to nonlinearities associated with the travelling wave dynamics, rather than the piezoelectric material itself, since lower piezoelectric strain response typically occurs at increasing electric field for both bulk [31] and thin film [32] PZT. The resulting micrometer-scale travelling wave amplitudes achieved are well above the level required to drive a frictionally-coupled rotor from the actuated stator.

The impact of tether compliance on stator performance was next explored. The tethers are necessary elements that provide mechanical support for the stator while also allowing electrical traces to be routed between the stator electrodes and off-stator bond pads. However, the tethers can also affect stator vibrations by mechanically loading the moving structure and providing a path for energy loss to the surrounding substrate. In conventional microresonators, loading of the resonant structure is typically reduced by connecting the anchors to nodal points of the resonator, and by matching resonant frequencies between the anchor and resonator to minimize impedance mismatch between the two mechanical elements. For the case of our PZT stators, the impact of the tethers on stator performance is complicated by the lack of nodal points for the annular travelling wave. Furthermore, because the tethers can potentially make direct contact with the attached rotor, tether mode shape and amplitude must also be taken into consideration. To address this latter issue, numerical models were used to predict the mode shapes for devices covering the full range of tether lengths ($800\text{--}2000\text{ }\mu\text{m}$), with the results shown in Figure 12. As seen in this figure, as the tether length increases the maximum stator amplitude also increases. However, for tethers longer than 1.6 mm , the position of maximum amplitude moves from the annular stator ring to the tethers. In addition to reducing the amplitude of the stator, the higher tether amplitudes can also impede contact between the stator surface and rotor, thereby preventing effective momentum transfer. The predicted trend presented in Figure 12 was also observed experimentally, with measured traveling wave amplitudes shown in Figure 13. A maximum amplitude of nearly $3\text{ }\mu\text{m}$ was achieved for a tether length of 1.6 mm , consistent with the numerical prediction.

C. Rotor actuation

Small motor footprints are desired for integration into miniature devices and systems, and to reduce manufacturing cost, which scales with motor area. To this end, we chose to further characterize stators with $800\text{ }\mu\text{m}$ long tethers, rather than the $1600\text{ }\mu\text{m}$ tether design that provided the highest amplitude. While the traveling wave amplitude for this design ($1.4\text{ }\mu\text{m}$ at 80 V) was approximately half the maximum value, it remains sufficient for robust rotor actuation. Using the $800\text{ }\mu\text{m}$ tether design, 4 mm diameter glass rotors were positioned on fabricated stators for experimental characterization. Each rotor was fabricated with a dry film photoresist post patterned in the center of the disk. The post was inserted into the inner stator opening, providing a mechanical constraint to prevent excessive lateral shifting during operation. Each rotor was placed in contact with the Ni layer on the backside of the PZT stator, opposite the interdigitated electrodes, to prevent electrode damage due to frictional contact or potential resistive contact across the electrodes due to mobile charges on the glass surface. The continuous Ni film serves as a friction layer during motor operation. When

driving the stator with a preload force between the rotor and stator surface defined by the weight of the rotor itself, the rotor was observed to vibrate under the influence of the generated traveling wave, with increasing vibration amplitude as the input voltage was increased up to 80 V, but without defined rotation. This result was anticipated, since rotation requires that sufficient normal force be applied between the surfaces in frictional contact. To increase preload force, additional glass rotor structures were sequentially laminated on top of the original rotor, increasing the total rotor mass from an initial value of 9 g up to a maximum of 64 g. The resulting measurements of rotor rotation speed under varying preload conditions are presented in Figure 14. For preload forces above 196 mN (20 g rotor mass), initial rotor rotation occurred at an input voltage of 40 V, corresponding to a traveling wave amplitude of approximately 200 nm. Above 40 V, the rotation speed was found to increase linearly with input voltage. Furthermore, by reversing the input voltage sequence to reverse the propagation direction for the travelling wave, stable bi-directional motion was achieved.

Using the rotor speed data at 80 V actuation for each preload state, the relationship between rotor speed and preload force is presented in Figure 15. Maximum rotor speed was achieved for a preload force of 323 mN from a 33 g rotor. At very low preload force values, frictional coupling between the rotor and Ni coated PZT surface is insufficient to prevent slipping, resulting in low rotation speeds. As the preload approaches the optimal value of 33 g, the increasing normal force resulting from the rotor weight reduces slipping, thereby enhancing the rotor rotation speed. When the applied preload exceeds the optimal value, it is believed that excessive loading of the stator occurs, with the rotor shifting the resonance frequency of the coupled system while also mechanically constraining the traveling wave amplitude. Both behaviors are assumed to degrade the travelling wave amplitude and reduce the maximum rotor speed. The motor stall torque can be estimated as the product of the frictional contact force and the stator radius [33]. Assuming a coefficient of kinetic friction between the nickel-coated PZT stator and glass rotor equal to $\mu_k = 0.5$ [34], and taking into account the average stator radius of 3.1 mm and a normal force of 323 mN, a maximum stall torque of 501 mN · mm was estimated for the tested motors.

The measured torque performance compares well against other ultrasonic micromotor implementations. For example, miniature unidirectional ultrasonic motors with total volume below 10 mm³ have recently been reported with torque:volume ratios between 1-10 [35]–[38], compared to over 60 for the bulk bi-directional motors explored here. However, we note that in the present motor implementation, the rotor rests on the ultrasonic stator element with a preload force defined by self-weight alone, and with the photoresist post in the rotor center providing the only mechanical constraint maintaining rotor position during motor operation. As a result, performance metrics such as wobble and axial stability could not be readily extracted for these devices. Furthermore, measured values of torque and speed are likely higher than would be observed for a fully integrated motor in which frictional losses due to the preload mechanism are expected. Thus further integration of the bulk PZT ultrasonic travelling wave motors is needed to provide a detailed view of motor performance.

CONCLUSION

Millimeter scale traveling wave ultrasonic rotary motors have been fabricated from bulk PZT. The motor stators employ a simple fabrication technique based on micropowder blasting of homogeneous PZT sheets that is made possible by the use of single-sided transverse interdigitated electrodes for bendingmode actuation, together with a differential quadrature drive scheme to generate the desired traveling wave dynamics. The resulting devices are believed to represent the smallest demonstrated bulk PZT traveling wave motors capable of bidirectional rotary motion, and may be further miniaturized to sub-millimeter dimensions based on the current fabrication limitations for the micropowder blasting process. Optimal conditions for poling the stator elements were identified, and the impact of stator tether dimensions on traveling wave generation was explored, enabling the design and fabrication of motors exhibiting rotary speeds up to 30 rpm with maximum stall torque over 500 mN · mm. With further development to fully integrate the stator/rotor pairs with a mechanism for defining the desired preload force, the bulk PZT micromotors offer performance suitable for a range of applications such as rotary actuators for intravascular imaging probes and miniature robotic platforms.

Acknowledgments

The authors would like to thank Prof. Balachandran and the Vibrations Laboratory at the University of Maryland for supporting scanning LDV experiments. We acknowledge the support of the Maryland NanoCenter and its FabLab. This work was supported by NIH grant R21EB019161.

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Fig. 1.

Stator surface points follow elliptical paths, transferring momentum to a coupled stator and resulting in stator rotation opposite the direction of wave propagation.

Fig. 2.

Actuation topologies for generating B03 traveling waves with wavelength λ , and normalized voltages applied across the piezoelectric elements. (a) Conventional thickness-mode actuation using a bimorph with a bottom grounded electrode, and (b) transverse interdigitated actuation of a homogeneous piezoelectric stator with top electrodes only, with effective voltage amplitude enhanced by the differential signals inherent to this actuation scheme.

Fig. 3. Bulk PZT stator (i.d. 2080 μm , o.d. 4120 μm), and magnified view of the transverse interdigitated electrodes (right) used for device actuation.

Fig. 4.

Stator fabrication process, comprising (a) bonding of a PZT sheet to a Si handle wafer using wax, (b) lift-off metallization of Al electrodes (mask 1), (c) micropowder blasting to fabricate a glass hard mask using dry film photoresist (mask 2), (d) bonding the glass mask to PZT using sheet wax (e) micropowder blasting to define the stator geometry, and (f) stripping of resist and wax to release the final devices.

Fig. 5.

Glass rotor fabrication process: (a) bonding 100 μm thick glass cover slip to a handle wafer with wax, (b) micropowder blasting to define the rotors, (c) lamination and (d) patterning of permanent dry film photoresist to define posts that seat into the inner openings of the stators, and (e) rotor release.

Fig. 6.
Image of an assembled PZT stator glass rotor device.

Fig. 7.
Comparison of using DFR mask and hard mask on the capacitance of etched cantilevers.

Fig. 8. Poling conditions of the stator showing that effective poling is obtained by first depoling the PZT by heating above Curie temperature (T_c) and then poling using optimized conditions.

Fig. 9. Comparison of analytical and experimental resonant frequency data for stators with 4.1 mm ring diameter and varying tether lengths.

Fig. 10.

Scanning LDV measurements of a B_{03} traveling wave in a bulk PZT ring stator driven with transverse interdigitated electrodes. The dot traces traveling wave propagation for a quarter period under both (a) clockwise and (b) anti-clockwise operation.

Fig. 11. Traveling wave amplitude as a function of voltage applied across the interdigitated electrode pairs for an unloaded stator with 1 mm tether length.

Fig. 12.

B_{03} mode shapes and eigenfrequencies (f) for 4.1 mm o.d. and 2.8 mm i.d. stators with varying tether lengths (L). As tether length increases, the radial position of peak amplitude (r_{peak}) moves from the outer edge of the annulus (r_{od}) to the tethers, resulting in $r_{\text{peak}}/r_{\text{od}} > 1$ for $L > 1 \text{ mm}$.

Fig. 13. Traveling wave amplitudes for unloaded stators with varying tether lengths when actuated at 80V.

Fig. 14. Characterization of the dependence of rotor speed on the traveling wave amplitude measured by varying the actuation voltage.

Fig. 15.
Rotor speed dependence on rotor self-weight highlighting the optimum weight.