Letters

Directional Acoustic Underwater Thruster

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***Abstract*—This study describes a tested prototype for a controllable directional underwater thruster with no moving parts. During operation, a high-intensity acoustic wave creates directional water jets and the device moves itself in the opposite direction. When the underwater thruster moves along a non-vertical angle, it can produce straight backward thrust of 2.3 mN and lateral thrust of 0.6 mN in parallel with the device surface, with a total thrust-to-weight ratio of 2:1. To enhance the acoustic streaming effect, a self-focusing acoustic transducer (SFAT) with air reflectors is used to focus the acoustic wave.**

I. Introduction

In the field of earth and space exploration, micro-thrusters are among the recent applications for micro-electro-mechanical system (MEMS) technologies [1]–[3], because MEMS technologies can reduce the size of the devices and lower the job costs. With its simple structure, our underwater thruster exhibits excellent potential for monitoring and controlling applications for water in natural and urban environments as a model micro-thruster [4]. A few types of underwater thrusters have already been reported. A conventional thruster is ignited by certain heating elements that give shot thrusts, which requires expensive and complicated fabrication processes [5], [6]. In contrast, acoustic thrusters apply the concept of high-intensity acoustic waves to produce bulk fluid movements. This method suggests that the underwater thruster could contribute significantly to the development for an autonomous surface/underwater vehicle, especially where maneuverability is required. Among its immediately attractive attributes are the thruster's silent operation (in and below hearable frequencies) and its low-maintenance design (simple, robust, and free of moving parts). Nozzle-type ejectors have been developed for generating the water jets with either thermal actuation [Fig. 1(a)] or lead zirconate titanate (PZT) piezoelectric actuation [7]. However, nozzle clogging and complicated device structures still limit its usefulness in real applications. A nozzle-less underwater thruster with a relatively simple structure can be built using self-focusing acoustic transducers (SFATs), and an example of the technology based on SFAT devices has been developed by Yu *et al.* These underwater thrusters were designed to move only in one direction. The direction cannot be changed during operation [8], [9]. A directional droplet ejector based on the same principle was also developed at that time, and it demonstrated droplet movement with non-vertical angles to the device surface [10]. In this paper, we discuss a controllable directional acoustic underwater thruster employing both of these technologies, which can propel itself and change direction without any moving parts.

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II. Theory and Experimental Procedure

The mechanism of acoustic streaming can be imagined as follows: imagine that a body of fluid consists of many small sponge balls. When the thruster emits a pulse of acoustic waves, the momentum flux transmitted through one such sponge ball will exit at a lower level. This results from the attenuation of acoustic flow energy, determined by the fluid viscosity [11]. Because of the conservation of momentum, a momentum gradient is created across the ball and generates a nonzero time-averaged mass-flow effect resulting in a motion of the ball. Constant force in the sound field starts an acoustic streaming jet that will be enhanced by increasing sound field intensity. The SFAT design then was used to enhance the thrust performance by focusing the acoustic waves. In our design, the active regions of the SFAT device are divided into 90° sectors, which produce not only strong, but also asymmetric acoustic waves. This high-intensity asymmetric acoustic wave will produce a steady body force with a tilted angle, resulting in a powerful non-vertical directional thrust.

Fig. 2 illustrates the fabrication flow of the sectored SFAT thruster on a PZT sheet. The fabrication process starts with a 127-μm-thick PZT substrate. Using front-to-back alignment marks, nickel electrodes are patterned on both sides of the PZT sheet such that the top and bottom SFAT electrodes overlap each other. The nickel film is etched with a 3:1 solution of $HCl:HNO_3$ for 20 s. After this, a 3-μm-thick photo-resist (AZ 4330, AZ Electronic Materials USA Corp., Branchburg, NJ) is patterned, followed by the first layer of Parylene-C deposition to form the Fresnel air-reflector lens structure shown in Fig. 2(a). The photoresist in the air reflector [Fig. 2(b)] is removed first by acetone, then by isopropyl alcohol, and by supercritical drying through the releasing holes [Fig. 2(c)]. After that, another Parylene layer is deposited to seal the holes. Meanwhile, a silicon substrate is anisotropically

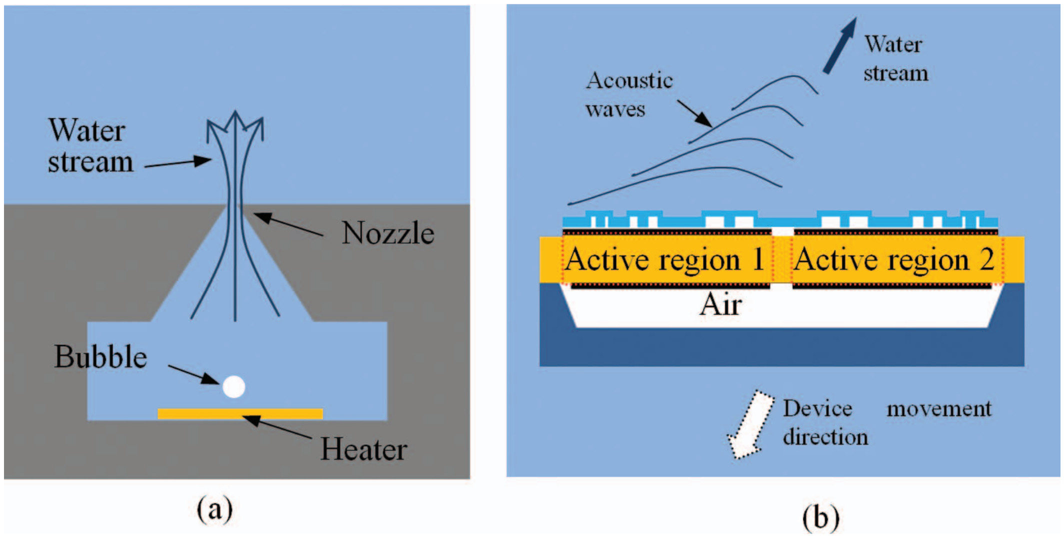

Fig. 1. (a) Schematic diagram of a nozzle-type ejector with thermal actuation. (b) Schematic diagram of the operation principle of the directional acoustic thruster. When the left active region of a sectored SFAT is actuated, it will produce a steady body force tilting to the right, resulting in directional thrust moving the ejector to the left.

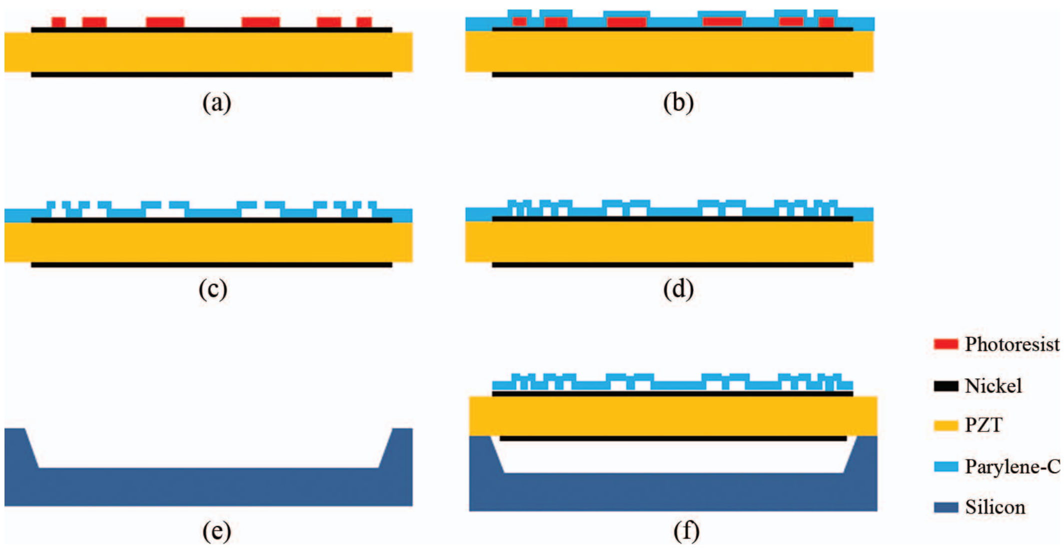

Fig. 2. Schematic illustration of the fabrication process: (a) pattern nickel electrodes on the top and bottom of the PZT sheet, followed by coating and patterning a 3-µm photo-resist layer for the sacrificial layer. (b) Deposit and pattern the first Parylene-C layer as the lens material. (c) Remove the photo-resist for several hours. (d) Deposit another 4- to 5-µm-thick layer of Parylene-C to seal the release holes to complete the lens. (e) Form 200-µm-deep chambers on a silicon wafer. (f) Bond the PZT sheet to the Si wafer with epoxy.

etched using hot KOH to form the chamber spaces. Finally, the silicon chamber is bonded on the back side of the PZT sheet with epoxy.

III. Results and Discussion

Fig. 3(a) shows the view of the whole device and Fig. 3(b) presents the detail of the device with the releasing holes. Fig. 3(c) shows the scanning electron micrograph (SEM) of the cross-sectional view of the Fresnel air-reflector lens structure. A single thruster measures 6 × 6 mm.

The operating principle of SFAT is that when RF power is applied to the SFAT device with the frequency corresponding to the thickness mode resonance of the PZT, strong acoustic waves are generated, penetrating through the Fresnel lens, interfering with each other and focusing on the focal point to form a high-intensity acoustic beam [12]–[14]. The high-intensity acoustic waves produce a steady body force because of the acoustic streaming effect, and this drives the water against the device, moving the device itself in the water. The size of each Fresnel ring is designed and optimized by a simulation program, and the radii (r_n) of the annular electrodes must satisfy [15]

$$\sqrt{r_n^2 + F^2} - F = \frac{n\lambda_{\mathrm{w}}}{4}, \qquad (1)$$

where $n = 1, 3, 5, ..., 2n + 1, ...$, r_n is determined by acoustic wavelength in the liquid (λ_{w}) and the designed focal length (F). Because of the quarterly sectored SFAT de-

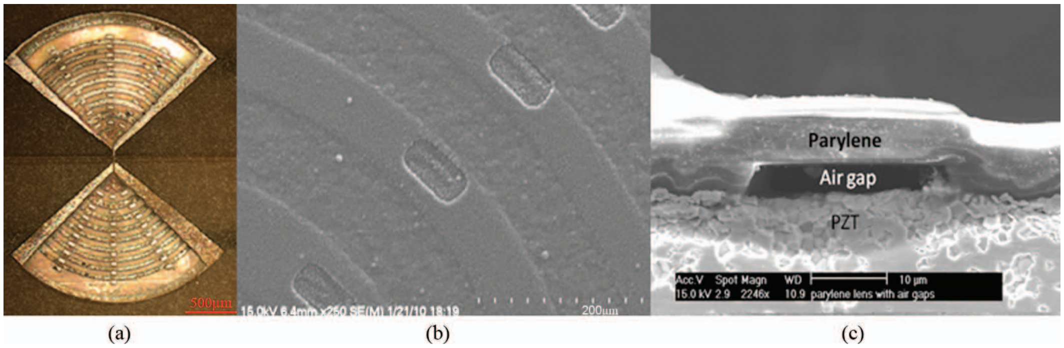

Fig. 3. Optical and SEM photos of the SFAT device. (a) The top view of the whole device. (b) The top view of the Fresnel air-reflector lens structure and the releasing holes. (c) The cross-sectional view of the cut-away Fresnel air-reflector lens structure.

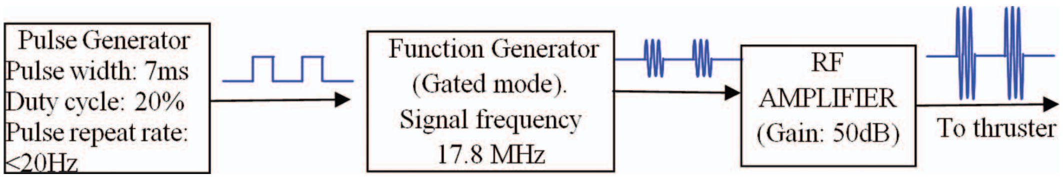

Fig. 4. Diagram of the testing setup to supply the burst RF driving signal to the thruster.

sign, a high-power acoustic wave beam at the focal point becomes asymmetrical and a non-vertical water stream shoots out from the focal plane, resulting in non-vertical device movement. The pair of sectors is set in a symmetrical manner and can be actuated separately or simultaneously to move the device in an angled, or straight backward direction, respectively.

A burst of 17.8 MHz signals (the fundamental thickness-mode resonance frequency of the 127-μm-thick PZT) with peak-to-peak voltage of 140 V, pulse width of 7 ms, and duty cycle of 20% were supplied to drive the transducer (Fig. 4); a CCD video camera system captured the thruster movement. The device was hold by soft electrode wires (coated with Parylene-C to prevent current leakage) in the water and the movement was captured with the camera (Fig. 5). The interval of the two pictures is 1/30 s; Fig. 5(a) shows the device suspended by conductive wire in the water. When both sectors of the thruster were actuated, the thruster moved straight backward as shown in Fig. 5(b); the angle of movement was around 14°. The thrust direction was demonstrated by microspheres with a diameter of 97 μm (Thermo Fisher Scientific Corp., Pittsburgh, PA) suspended in the water. When both sectors were driven [Figs. 6(a) and 6(b)], the microspheres were pushed away vertically, because the acoustic wave was symmetrical [shown in the simulation results in Fig. 6(c)]. When only the right transducer sector was actuated [Figs. 6(d) and 6(e)], the microspheres were pushed away from the device, tilting to the left with the angle of approximately 15°, demonstrating the non-vertical directional thrust. Similarly, when the left sector was actuated, the device moved, tilting to the left. The simulation results [Fig. 6(f)] indicate that when one sector of the device is activated, the high-intensity acoustic wave beam at the focal point is nonsymmetrical, resulting in a non-vertical water stream to thrust the device with a tilted angle. We measured the weight of our devices and the thrust forces were calculated through a pendulum system by actuating a single quarterly sector of SFAT. The thruster produced backward thrusting force of up to 2.3 mN; the thrusting force to the side was 0.6 mN.

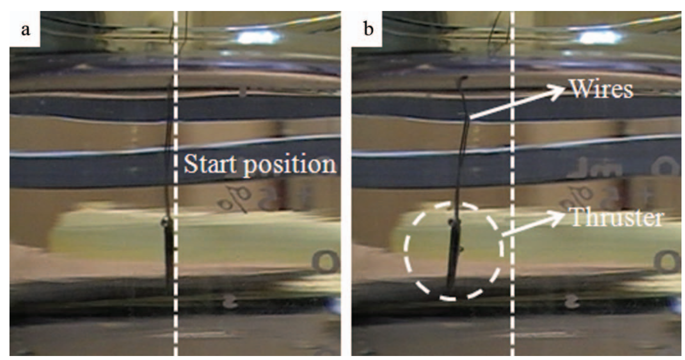

Fig. 5. The device was hung by electrode wires in the water: (a) photo of the device at initial position before thrusting; (b) snapshot photo of the thruster motion that pushes the device to the left.

IV. Summary

In summary, we developed an underwater thruster that extends previous SFAT thrusters' functions to drive it in three directions: straight backward or with a left or right non-vertical angle. The directional acoustic thrusters provide a unique driving mechanism that has controllable direction with no moving parts. The thruster has a high thrust-to-weight ratio of 2:1. This acoustic thruster has

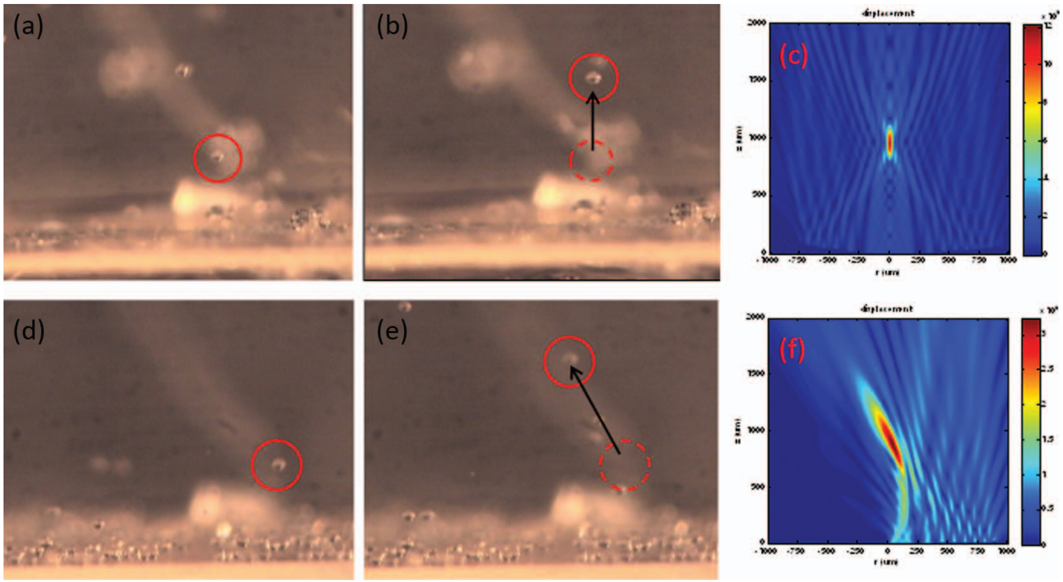

Fig. 6. The thruster force testing results and the simulation results. (a) and (b), after both SFATs are activated, microspheres (in the solid circles) are pushed away vertically by symmetrical acoustic waves. (The dashed circle indicates the starting position of the microsphere.) (c) Simulation result for both sectors being actuated. (d) and (e), when only the right SFAT is activated, microspheres were pushed away vertically and backward to the left. (f) Simulation result of the right sector only being actuated. In simulation results (c) and (f), the color indicates the particle's displacement of acoustic waves.

great potential for biomedical applications and environmental actuator applications.

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