

Figure 1 Composite transducer used in experiment.

## 2. Acoustic streaming by high-frequency ultrasonic waves

Fig. 1 shows the basic configuration of the transducer employed in the experiment. A ZnO-film of  $13\mu\text{m}$  thickness is deposited on a cover glass of  $120\mu\text{m}$  thickness by RF magnetron sputtering, and sandwiched with Al electrodes of  $0.2\mu\text{m}$  thickness. The radiation area of the transducer is  $0.5 \times 0.5\text{mm}^2$ .

Since the cover glass is much thicker than the ZnO film, the unloaded transducer behaves like a high- $Q$  multi-mode resonator. Although the  $Q$  factor is a little reduced by water-loading, it still remains relatively large. Because of its high  $Q$  factor, the transducer is easily impedance-matched with an electrical source, which results in an efficient radiation of ultrasonic waves into liquid. The minimum electrical to acoustic conversion loss of 2.8dB was achieved by optimised design of the transducer.

It may be noted that although the transducer possesses quite narrow bandwidth due to its high  $Q$  factor, its transit time of the order of  $1\mu\text{s}$  is still much faster than that for liquid flow.

Fig. 2 shows the water surface lifted by acoustic streaming with an input electrical power of 630mW at 278MHz. It is seen that the water surface above the transducer was lifted to 2cm when the water depth was about 2mm.

If the water depth was reduced to less than 1mm, water was ejected into air as droplets to reach a few centimeter high until the reservoir became empty.<sup>(2)</sup>

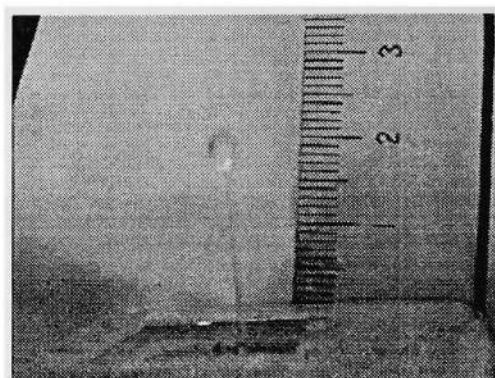


Figure 2 Water surface lifted by acoustic streaming.

## 3. Micro-manipulator

Fig. 3 shows the basic configuration of the proposed two-dimensional micro-manipulator consisting of an ultrasonic transducer array. When one transducer is excited, liquid above the transducer begins to flow toward the lateral direction as well as the vertical direction: small particles are carried with the induced liquid flow. This suggests that properly exciting respective transducers simultaneously, one could manipulate a small particle toward the specified lateral direction as shown in Fig. 3 by the induced liquid flow.

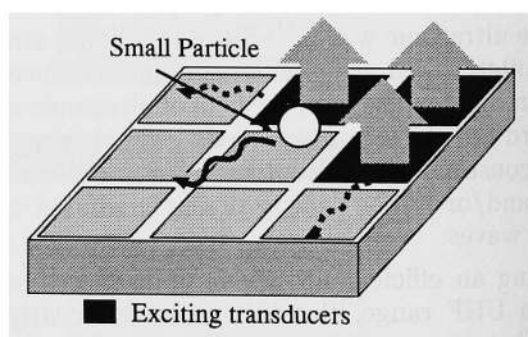


Figure 3 Proposed two-dimensional micro-manipulator.

It may be of importance to consider the situation where a small particle is placed above the edge of a transducer as shown in Fig. 4. Although the particle is to move outward the transducer by acoustic streaming, it is sometimes circulated and trapped

near the transducer by the liquid-convection; liquid flown out from the transducer region should be supplied from its surrounding area.

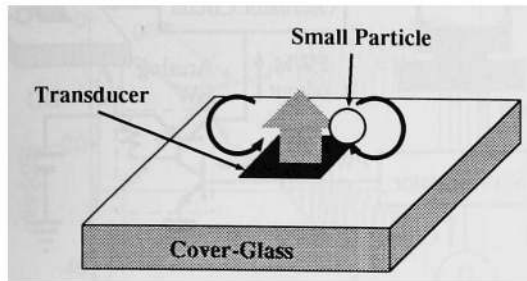


Figure 4 Trapped particle by circulating liquid.

To deal with this problem, a two channel structure shown in Fig. 5 is proposed. As shown in the figure, liquid circulates through the small holes and the paths indicated by the arrows, where one hole is prepared just above the transducer and the others far from the transducer.

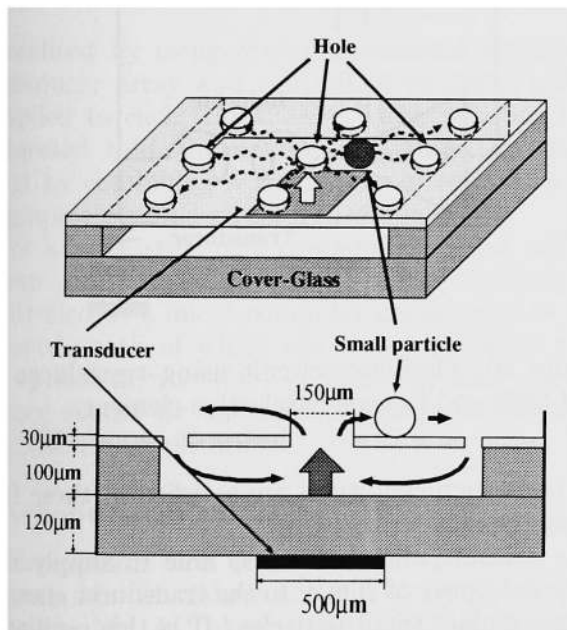


Figure 5 Two channel structure for micro-manipulator.

Fig. 6 shows a glass sphere of  $200\mu\text{m}\phi$  manipulated by the structure shown in Fig. 5, where water is used as liquid. As can be seen, the glass sphere placed near the hole (Fig. 6(a)) was transferred outward the transducer without being trapped (Fig. 6(b)) by circulating water. An electrical power of 20mW being applied to the

transducer, the glass sphere moved at a speed of about  $500\mu\text{m/s}$ . The result shows that the micro-manipulator for small particles can be realised by the two channel structure fabricated on a two-dimensional transducer array, where water circulation is skillfully controlled not to trap small particles.

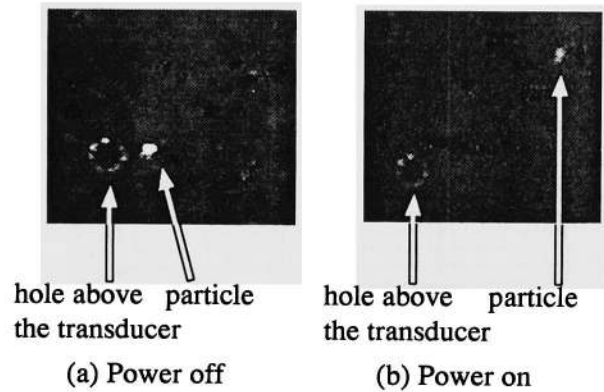


Figure 6 Manipulation of a glass sphere.

#### 4. Micro-pump

Employing such a structure in which a topographic liquid channel is piled up on the two channel structure shown in Fig. 5, a one-dimensional liquid micro-pump could be developed.

After the topographic liquid channel was fabricated by stacking micromachined Si wafers, it was attached to the two channel structure as shown in Fig. 7. As a result, liquid was clearly seen circulating within the channel. This suggests that the acoustic streaming could also be applied to the development of liquid micro-pumps.

The cascade-connected unit cell structure shown in Fig. 8 would be effective in letting liquid flow toward a specified direction. The direction of liquid flow can be reversed by exciting every two adjacent transducers (shaded ones in Fig. 8).

#### 5. Driving Electrical Circuit

For a micro-manipulator based on a two-dimensional transducer array, electrical power applied to each transducer should be controlled precisely and independently so that liquid can be flown into a specified direction. Because of their high  $Q$  factor, the transducers possess a very narrow operation bandwidth. This makes it quite difficult to drive all the transducers by a single oscillator: there is a small deviation in the resonance frequen-

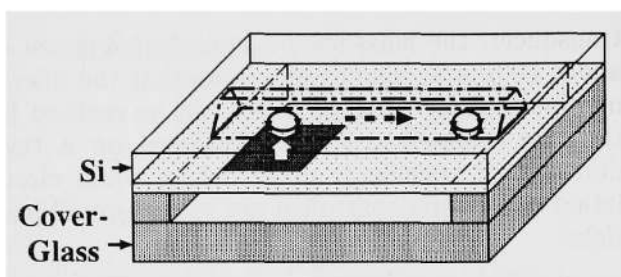


Figure 7 Unit cell of liquid channel used in experiment.

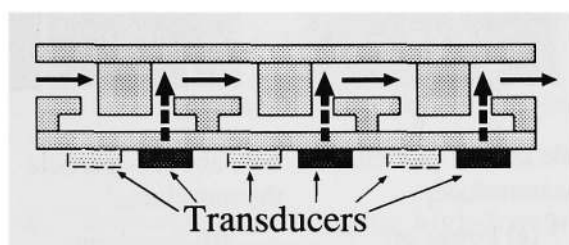


Figure 8 Cascade-connected unit cell structure.

cies of the transducers, which arises from the non-uniformity in ZnO film thickness.

From this point of view, we investigated a method of exciting the transducers, in which each transducer is used as a feed-back and frequency-selective element in oscillator circuits. Preparing such oscillator circuit for every transducer, one could control the intensity of acoustic streaming by switching or pulse-width-modulating the DC voltage supplied to the circuit. This can be done using an analog-switch array controlled by a micro-computer (see Fig. 9).

Fig. 10 shows the oscillator circuit developed for driving a transducer, which employs commercially available RF amplifier NEC  $\mu$ PC1677C (the maximum output is 19.5dBm with a supplied voltage of 5V and current of 50mA).

Fig. 11 shows the open-loop response of the oscillator. Because of the multi-mode resonance of the transducer, the phase crosses zero at a lot of frequency points, where the gain takes a local maximum. This means that the oscillation occurs at one of such frequency points. It may be noted that the oscillation frequency jump, which is often come across in a multi-mode resonator, scarcely affects the intensity of induced acoustic streaming. The inductance of about 100nH and capacitance of about 6.5pF in the circuit were chosen so that

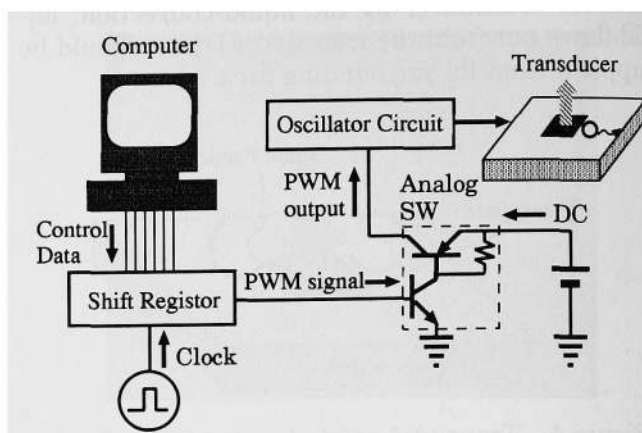


Figure 9 Pulse-width-modulation circuit for micro-manipulation.

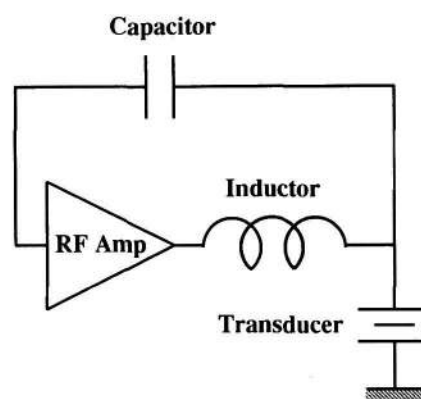


Figure 10 Oscillator circuit using transducer as feed-back and frequency-selective element.

the oscillation conditions are satisfied at these frequency points.

As a result, the circuit was able to supply the electrical power of 20mW to the transducer enough to manipulate small particles. It is this oscillator circuit that successfully manipulated a glass sphere as shown in Fig. 6.

## 6. Conclusion

This paper has proposed the application of acoustic streaming effectively induced by high-frequency ultrasonic waves to the development of micro-actuators such as micro-manipulators for small particles and micro-pumps for liquid.

It has been shown that the micro-manipulator

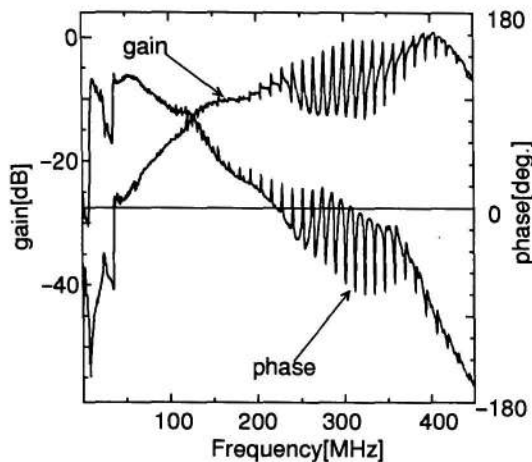


Figure 11 Open-loop response of oscillator.

is realised by using a two-dimensional ultrasonic transducer array and controlling electrical power supplied to each transducer. The result has also suggested that the micro-pump could be developed by combining a transducer array with a topographic channel structure for liquid flow.

As a next step, the cascade-connected micro-pump and two-dimensional micro-manipulator controlled by a micro-computer are going to be developed, both of which are to be combined with an optical microscope. In addition, their performance should be understood more quantitatively for practical applications.

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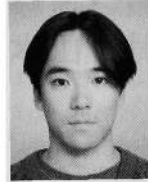
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