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Double-Parabolic-Reflector Ultrasonic Transducer with Fluid Medium (Fluid-type DPLUS)

Kyohei Yamada[1‡], Weiquan Wang[1], Kang Chen[1], Susumu Miyake[1], and Takeshi Morita[1, 2] ([1]Grad. School of Frontier Sciences, The Univ. of Tokyo, [2]School of Eng., The Univ. of Tokyo)

1. Introduction

High-frequency, high-power ultrasonic applications related to liquid have been attracting attention recently. For example, ultrasonic cleaners can improve cleaning speed by applying ultrasonic vibration to a cleaning solution. It is widely used to remove cutting oils, abrasives, and mold release agents from machine parts, molds, tools, etc. Recently, the removal of particles smaller than 20 nm from silicon wafers has become particularly important due to the miniaturization of semiconductor patterns.[1)] High acoustic pressure is required for effective cleaning: though the sound pressure higher than the cavitation threshold results in defects in semiconductor surface patterns. To utilize high-power ultrasound and avoid damaging the surface patterns, driving at higher frequencies (several megahertz) is necessary, of which the cavitation threshold is higher (several hundred kilopascals).[2)] That is why high frequency, high power ultrasound generation is promising.

Another example is a generation of microbubbles and microcapsules. They have many applications, such as thermal storage particles, ultrasonic contrast agents, drug delivery carriers, etc. Several studies have been conducted about microbubbles and microcapsules generation methods assisted by ultrasonic transducers. One study generated microbubbles or microcapsules by irradiating ultrasonic waves at the gas-liquid interface.[3)] Another study reported the microcapsules generation by irradiating ultrasonic waves to produce emulsions from two types of liquids[4)]. In these methods, however, the driving frequencies of ultrasonic transducers were around 20 kHz. Higher frequency (several megahertz) ultrasonic radiations are strongly required because they could make the smaller size of bubbles and capsules.

In these situations, novel ultrasonic devices have become necessary to generate high-frequency, high-power ultrasonic waves in a liquid medium. Generating such ultrasonic waves is difficult for conventional ultrasonic transducers, such as bolt-clamped Langevin-type transducers, of which the driving frequency is lower than several hundred kilohertz. It is true that DPLUS (double-parabolic-reflector ultrasonic transducer)[5)], has some suitable characteristics; it can radiate wideband (20 kHz-2.5 MHz), high-power (several megapascals) ultrasonic waves from the tip of its thin waveguide. However, the output ultrasound is localized at the tip of the waveguide, and large area output in a liquid medium might be difficult.

To generate high-frequency, high-power ultrasonic waves in a liquid medium, we propose "Fluid-type DPLUS" in this study. Fluid-type DPLUS has a similar shape to the conventional DPLUS, but the wave propagating medium is not solid but fluid. In this paper, we study water as a wave propagating medium. Any liquid or gas media can be accepted. Although not mentioned in this introduction, Fluid-type DPLUS may be useful also in airborne ultrasound applications.

2. Configuration and working mechanism

As shown in **Fig. 1**, the Fluid-type DPLUS is a z-axis symmetric structure consisting of a piezoelectric material and a fluid waveguide surrounded by a solid material. The fluid waveguide consists of the thin waveguide and the 1st (concave) and 2nd (convex) parabolic reflectors, which share the same focal point O. The working mechanism is as follows. First, an alternating voltage is applied to the piezoelectric ring, and its thickness vibration mode is excited, so the plane ultrasonic wave propagates into the fluid waveguide. Second, the plane wave is reflected by the 1st parabolic reflector and propagates toward the focal point O. Thirdly, the focusing wave is reflected by the 2nd parabolic reflector and then propagates with plane wavefronts

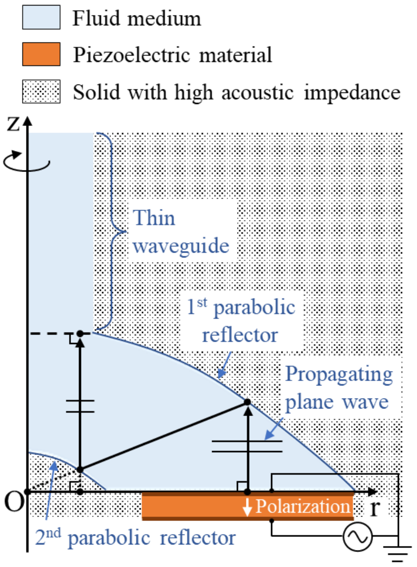

Fig. 1 Fluid-type DPLUS

into the thin waveguide. In this process, the energy density of the plane wave is amplified. The final output has multiple ways according to the actual applications. For example, if the application is ultrasonic cleaning, the output ultrasound is radiated from the tip of the thin waveguide. In the application of generating emulsions, two kinds of liquids are set as the thin waveguide medium, in which amplified ultrasonic wave propagates.

The proposed Fluid-type DPLUS has two advantages compared to the conventional DPLUS. One is the highly efficient energy amplification. It is because mode conversion—the transformation of dilatational and shear waves—does not occur in a fluid medium. As a result, the energy loss at the reflections becomes smaller. The other is that the unwanted high acoustic pressure around the 2nd parabolic reflector is prevented. The conventional DPLUS has two concave parabolic reflectors, so the propagating wave focuses before the 2nd reflection; thus, high acoustic pressure was generated around the focal point.[5] In Fluid-type DPLUS proposed this time, the ultrasonic wave does not actually focus on the focal point, so unwanted high acoustic pressure can be avoided. Especially in the case of liquid media, cavitation around the 2nd reflector could be avoided.

3. Finite element analysis of Fluid-type DPLUS

To verify the proposed principle for Fluid-type DPLUS, we conducted a finite element method (FEM) analysis with the software PZFlex (Weidlinger Associates, Los Altos, CA). In the simulation model, the fluid medium was water, and the piezoelectric material was PZT 5H. In order to eliminate the effect of the transmitted wave into the solid material, the acoustic impedance of solid material was set to $4.6 \times 10^9\ \mathrm{Pa \cdot s/m}$, which is 100 times as large as that of stainless steel, and the boundary condition of the outer surface was absorbing. The diameters of the 1st and 2nd parabolic reflectors were 40 mm and 2.0 mm, and the radius and length of the thin waveguide were 0.5 mm and 20 mm, respectively. A backing layer was adhered to the PZT ring surface to reduce the unwanted multiple reflections inside the PZT ring. The applied signal to the PZT ring was 10 Vpp, 1.7 MHz—near the thickness resonant frequency of the PZT ring, 5-cycle, sinusoidal wave.

Fig. 2 shows the simulated acoustic pressure distributions. First, the plane wave propagates to the 1st parabolic reflector, as shown in Fig. 2(a), and then the wave is reflected and propagates toward the focal point in Fig. 2(b). Next, the wave is reflected by the 2nd parabolic reflector, and the amplified plane wave is generated, as shown in Fig. 2(c). Finally, part of the plane wave propagates into the thin waveguide, and the other of the plane wave is reflected at the 1st reflector and goes backward, as shown in Fig. 2(d). This is because of wave diffusion on the way to the thin waveguide. The maximum acoustic pressure at the center point on the boundary surface between the thin waveguide and the 1st parabolic reflector was 0.30 MPa, which is 8.5 times as large as that of the incident plane wave, 35 kPa.

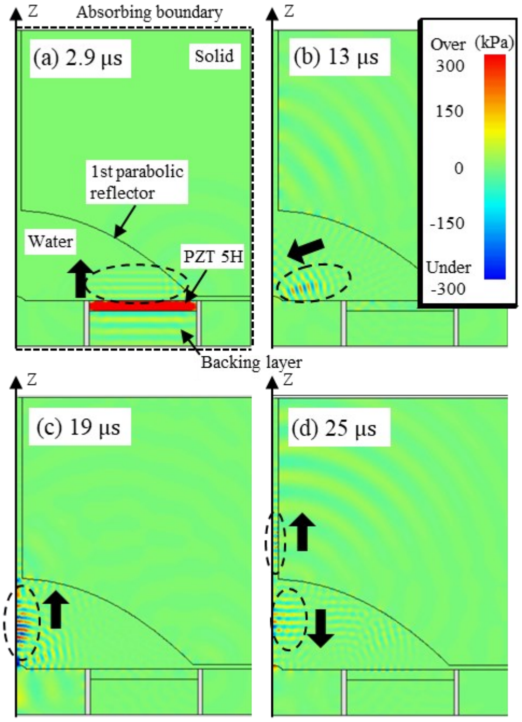

Fig. 2 Acoustic pressure distribution at (a) 2.9 μs, (b) 13μs, (c) 19 μs, and (d) 25 μs.

4. Conclusion and future work

In summary, Fluid-type DPLUS was proposed, and its principle was verified using FEM simulation. In the future study, the thin waveguide radius should be enlarged for all the ultrasonic waves to propagate into the thin waveguide at once. In addition, the effect of solid material surrounding the fluid waveguide should be studied for design optimization.

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