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Double ellipsoidal reflective surface for ultrasonic waves focusing into a thin waveguide

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1. Introduction

High power ultrasonic technology is used in various fields, and the Langevin transducer in particular has been widely used as a high power ultrasonic device. Langevin transducers have a resonant frequency in the band of several hundred kHz at most, basically 30~40 kHz, and can irradiate strong ultrasonic waves with high efficiency at this drive frequency. While Langevin transducers are useful when a single resonant mode is required in the frequency range of 30~40 kHz, it has been difficult to use Langevin transducers for MHz-band ultrasound or when multiple resonant modes are required. The purpose of this study is to solve these problems by constructing a MHz-band strong ultrasonic focusing device using a double ellipsoidal structure.

Double Parabolic refLectors wave-guided Ultrasonic transducer (DPLUS)[1,2] is a device that is based on a principle similar to that of this study. The appearance of DPLUS is depicted in **Fig. 1(a)**. It focuses ultrasonic waves that are generated from a piezoelectric element using two parabolic structures that share a focal point. These waves are then introduced into a thin rod waveguide to obtain high power ultrasonic vibrations at the tip of the thin waveguide. **Fig. 1(b)** illustrates that the longitudinal plane wave from the piezoelectric ring is first reflected by the first parabolic surface and subsequently focused toward the focal point owing to the parabolic nature of the surfaces. Finally, it is reflected by the second parabolic surface to introduce powerful ultrasonic waves in the plane wave into the thin waveguide.

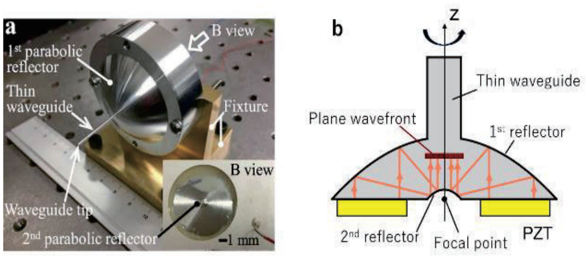

Fig. 1 DPLUS overview. (a) Photograph of DPLUS[1]. (b) Driving principle of DPLUS.

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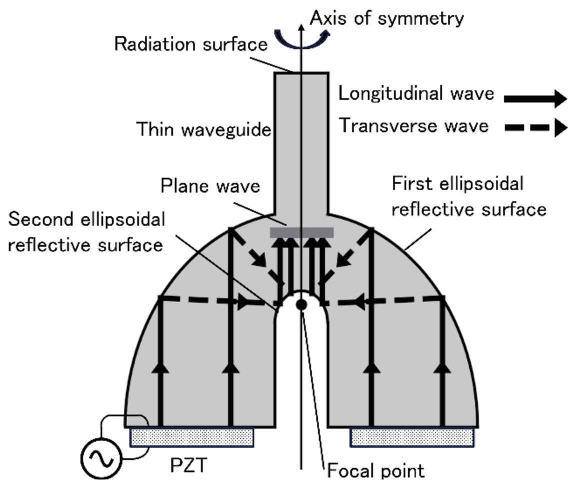

Fig. 2 Concept of the proposed double ellipsoidal surface device.

Two primary issues arise with DPLUS. The first issue is the loss caused by wave diffraction. The plane wave's straightness is dependent on the wavelength and the wave source area. Due to the size and frequency band of DPLUS, the effect of diffraction cannot be ignored. As a result, the waves do not propagate as illustrated in **Fig. 1(b)**. The second issue is the partial conversion of longitudinal waves into transverse waves upon reflection caused by longitudinal-transverse mode conversion. Even if we ignore wave diffraction, energy output is still lost by around 80% due to the mode conversion.

We propose the double ellipsoidal surface device that solves the problem of loss due to the mode conversion by using focusing process including the transverse waves. The focusing process illustrated in **Fig. 2** uses a ring-shaped piezoelectric element to generate longitudinal vibrations, while plane waves are directed towards the first ellipsoidal surface. As a result of reflection, transverse waves that emerge from the mode conversion collect at the focal point. Remarkably, most waves are reflected as transverse waves in regions where the angle of incidence ranges between 50~80 degrees on certain waveguide materials. The second ellipsoidal surface shares the same upper focal point with the first ellipsoidal surface. By an opposite reflection process, it transforms focused transverse waves into longitudinal plane waves. Introducing the resulting longitudinal plane wave into the thin waveguide facilitates the emission of high power ultrasonic waves from the thin waveguide's tip.

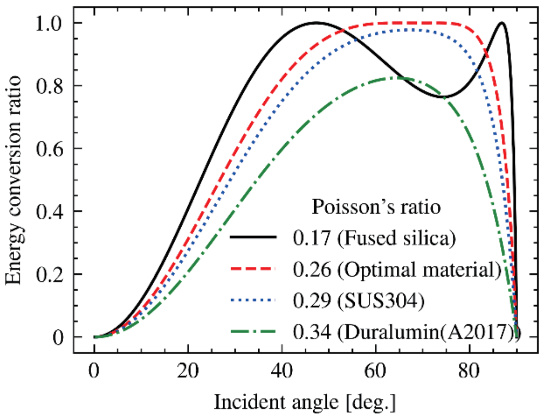

Fig. 3 Theoretical energy conversion ratio from longitudinal waves to transverse waves.

2. Working principle

Which type of reflective surface is required to focus transverse waves generated by mode converted longitudinal plane waves onto a single point? The equations were solved under the condition that the generated transverse waves collect to the focal point and the arrival time to the focal point is equal. The result shows that only ellipsoidal surfaces with specific shapes that depend on Poisson's ratio meet this requirement. This ellipsoid has a major to minor axis ratio of $c_d : \sqrt{c_d^2 - c_t^2}$, where the longitudinal and the transverse wave velocity are denoted as c_d and c_t, respectively.

As depicted in **Fig. 3**, the ratio of longitudinal waves converted to transverse waves in the mode conversion depends on the Poisson's ratio of the waveguide material and the angle of incidence, and materials with a Poisson's ratio close to 0.26 convert almost all waves to transverse waves at an angle of incidence of 50~80 degrees.

The energy efficiency was calculated using the ray tracing method in Python. This calculation only considers the mode conversion while neglecting the effects of wave diffraction, etc. According to the calculation results, the energy efficiency of DPLUS is 26.4%, while that of the proposed structure is 76.5%. Note that the calculations were performed using waveguide materials suitable for each focusing method. Duralumin (A2017) was used for DPLUS and SUS304 for the proposed structure.

3. Finite Element Analysis

Transient analyses of the proposed structure were performed using the finite element method software COMSOL. The piezoelectric ring is made of MT-18K PZT (Niterra Co., Ltd.) with a thickness of 1.3 mm, an inner diameter of 8.0 mm, and an outer diameter of 20.0 mm. The frequency was set to 1.581 MHz, which is the thickness resonance frequency of the piezoelectric ring, and five burst waves were applied at 2.0 V_{pp}. The material of the waveguide is SUS304, and the diameter of the thin rod waveguide is 1.0 mm.

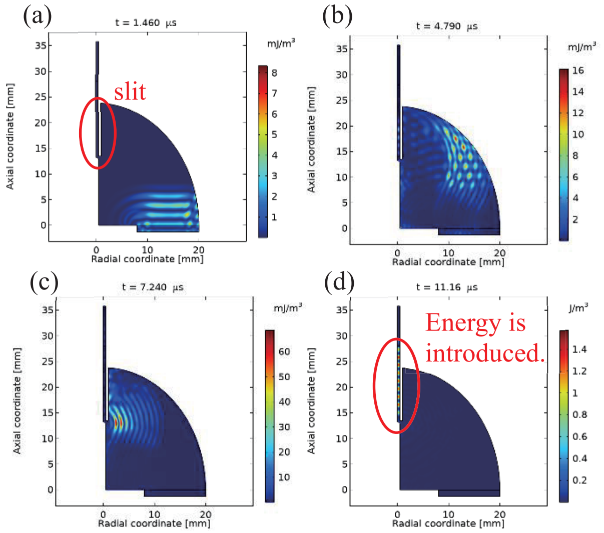

Fig. 4 Energy density distribution in transient analysis of the proposed structure at (a) 1.46 µs (b) 4.79 µs (c) 7.24 µs (d) 11.16 µs.

Fig. 4 shows the calculation results. It should be noted that the size of the second reflective surface is small (1.0 mm in diameter) compared to the wavelength of the longitudinal wave (3.66 mm), resulting in a notable wave diffusion effect after reflection. As shown in **Fig. 4(a)**, the diffusion effect is suppressed by inserting a slit at the base of the thin rod waveguide. Consequently, the energy that enters the waveguide from the piezoelectric ring is amplificated by a factor of 327 in energy density at the thin waveguide.

4. Conclusion and Future works

This study proposed an ultrasonic focusing structure with a double ellipsoidal surface to reduce loss in mode conversion. The calculation considering only mode conversion shows that energy can be introduced nearly three times more efficiently than DPLUS[1,2]. Finite element method calculations demonstrate that the waves are focused as designed.

As a prospect, the design will be modified to enhance the machinability. Machining the second reflective surface and the slit is challenging. To enhance the machinability of the second reflective surface, we intend to devise the structure.

References

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2) K. Chen, T. Irie, T. Iijima, and T. Morita, IEEE Trans. Ultrason. Ferroelectr. Freq. Control **67** [8], 1620–1631(2020).