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High-Power Ultrasound Introduction into Thin Tubular Waveguide of Tube-Type DPLUS

チューブ型 DPLUS による
円筒型導波路への高出力超音波の導入

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1.Introduction

DPLUS (Double-parabolic-reflectors ultrasonic transducer) can realize wideband (20 kHz to 2.5 MHz), high-intensity (several MPa) ultrasounds near the tip of the thin waveguide.[1,2] It is expected to be applied in a wide range of fields such as ultrasound therapeutics, medical imaging, ultrasonic tweezers[3], and so on.

However, the conventional DPLUS is difficult to receive the echo signal because the echo signal propagates the amplification mechanism in the opposite direction so that it is greatly attenuated. It hinders applications for medical imaging.

To solve this, we have previously proposed Tube-Type DPLUS[4], which is hollowed to allow the insertion of sensors such as a hydrophone, a thermocouple, and so on. We have designed two kinds of models shown in **Fig. 1** and compared them in simulation and experiment: (a) Model 1 and (b) Model 2. Model 1 has simply hollowed-out reflector, which is difficult to focus ultrasonic waves on account of reflection and refraction at the inner surface. On the other hand, Model 2 has the proposed reflector which can generate plane waves: in-phase waves in the axial direction. The simulation shows that the maximum underwater sound pressure generated by Model 2 is 1.6 times as high as that by Model 1 in burst excitation. [4]

In this previous research, however, the thin waveguide was only 10 mm long and we have not studied models with longer thin waveguides. In practical applications such as puncture needle-type ultrasonography[5], longer waveguides are more suitable because longer thin waveguides can be penetrated deeper into the body.

In this report, we simulate the acoustic power flow in Tube-Type DPLUS: Model 1 and Model 2 with 200 mm long thin waveguides. And then, the result is discussed in terms of the group velocity dispersion.

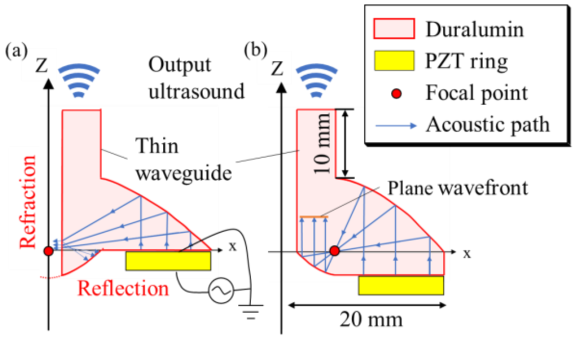


Fig. 1 Z-axis symmetric view of Tube-Type DPLUS: (a) Model 1, simply hollowed reflector; (b) Model 2, proposed reflector

2. Simulation

2.1 Simulation models

Fig. 2 shows simulation models; (a) is Model 1 and (b) Model 2. They have thin waveguides, whose length is 200 mm, inner radius (IR) is 1.0 mm, and outer radius (OR) is 2.5 mm. The applied voltage was 10 V_{pp}, 1.7 MHz, 5-cycle, sinusoidal wave. Damping in the waveguides was ignored. To reduce the unwanted multiple reflections inside the waveguides and PZT rings, backing layers were added and the boundary condition at the tip of thin waveguides was set to be the perfect absorbing.

Powers passing through surface 1, 100, and 200, the cross-sections of thin waveguides, were calculated utilizing the commercial finite element method (FEM) software, PZFlex (Weidlinger Associates, Los Altos, CA).

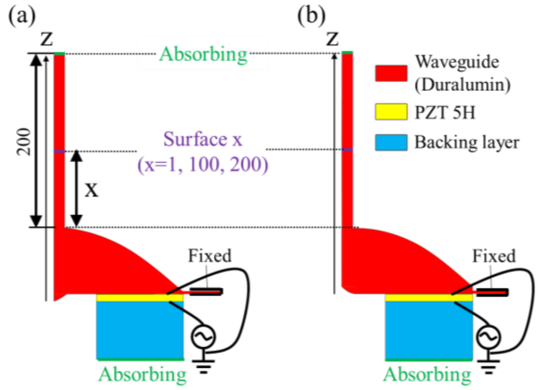


Fig. 2 Z-axis symmetric view of simulated models with 200 mm long thin waveguides; (a) Model 1, (b) Model 2

2.2 Simulation results

Fig. 3 shows powers passing through each surface at a thin waveguide in Model 1, and **Fig. 4** these in Model 2. From these results, Model 2 has better performance than Model 1 in two respects.

First, the power passing through surface 1 was 7.1 mW for Model 1 and 17 mW for Model 2, which is 2.4 times as large as that of Model 1. In addition, the power waveform of Model 2 shows less tailing than that of Model 1. Thus, Model 2 reflector can generate higher power ultrasound than Model 1 as in the previous research.

Second, the ratio of the maximum power passing through surface 200 to that through surface 1 is 0.52 for Model 1 and 0.71 for Model 2. This low attenuation in Model 2 is probably because the incident waves into the thin waveguide are in phase so that the effect of interference is small. Therefore, the Model 2 reflector is suitable for wave propagation at a longer thin waveguide.

Even in Model 2, however, the power peak value decrease after propagation, being undesirable in some applications such as ultrasonography. This phenomenon is because of group velocity dispersion, which causes waves to separate into three modes with different velocity as shown in Fig. 4: A, 2940 m/s; B, 1810 m/s; C, 3640 m/s.

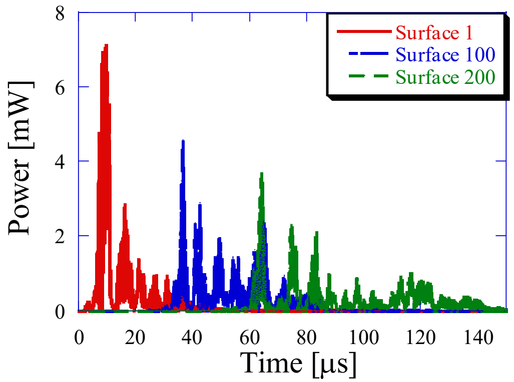
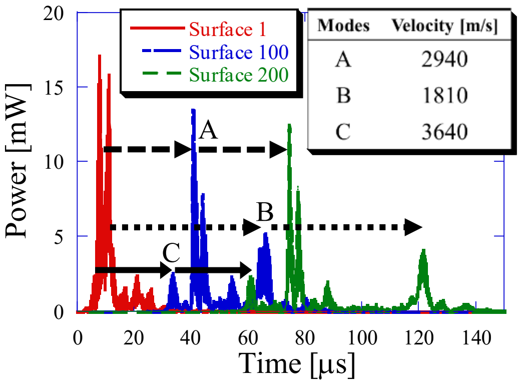


Fig. 3 Power flow at thin waveguide of Model 1



Modes	Velocity [m/s]
A	2940
B	1810
C	3640

Fig. 4 Power flow at thin waveguide of Model 2

3.Group velocity dispersion

Fig. 5 shows the first five group velocity dispersion curves in a tubular waveguide with the same dimensions as the aforementioned simulations (IR: 1.0 mm, OR: 2.5 mm). They were calculated by a software package, PCDSP, based on the Pochhammer Chree (PC) theory[6].

As Fig. 5 indicates, at 1.7 MHz, three modes can propagate in the thin waveguide with different group velocities: L(0,1), 3002 m/s; L(0,2), 1777 m/s; L(0,3), 3713 m/s. These results agree with the FEM simulations results; hence A is identified with L(0,1), B with L(0,2), and C with L(0,3).

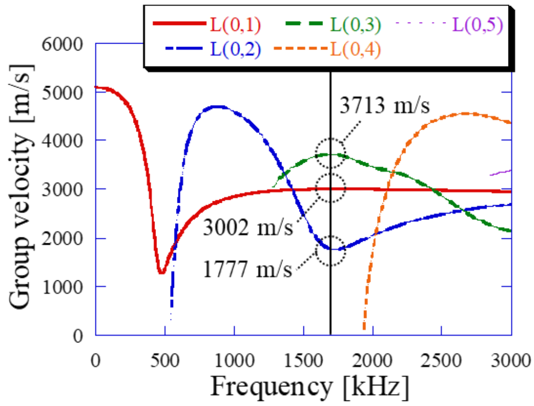


Fig. 5 Relations between frequency and group velocity in tubular waveguide (IR: 1.0 mm, OR: 2.5 mm)

4. Conclusion

In summary, Model 2 realizes low attenuation because in-phase waves can be input with a suitable reflector structure; however, velocity dispersion results in degenerated power peaks after long-distance propagation.

To overcome this problem, we are going to consider the excitation of only one mode, taking into account the mode shapes and the shape of incident waves into the thin waveguide.

Acknowledgment

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