Evaluation of Small Ultrasonic Probe using Lead Zirconate Titanate poly-crystal Film Deposited by Hydrothermal Method

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Abstract—The present study evaluates the characteristics of a small ultrasound probe using PZT polycrystalline film deposited by a hydrothermal synthesis method. With the hydrothermal synthesis method, PZT film is deposited only on the titanium by reaction in the solution. Utilizing this feature, a PZT polycrystalline film was deposited on the end face by a hydrothermal synthesis of a material with only its titanium wire end face exposed. This transducer was built into a small ultrasound probe and the characteristics were evaluated. As a result, we succeeded in the fabrication of a wideband ultrasound probe with a distance resolution of 32 μm, a frequency bandwidth of 50 MHz in the range of 25 to 74 MHz, and a fractional bandwidth of 99 %.

Keywords - hydrothermal method, PZT, ultrasound probe, evaluation

I. INTRODUCTION

Miniaturization of ultrasound probes in recent years has been promoted for medical ultrasonic diagnosis. Among their several applications, intravascular ultrasound diagnosis (IVUS), in which vascular cross-sectional images can be obtained by inserting a small ultrasound probe directly into a blood vessel instead of conventional diagnosis from the body surface, has been attracting attention [1-3]. However, an ultrasound probe for IVUS must be very tiny due to its insertion into the blood vessel and the yield ratio and development costs pose problems since adhesion of piezoelectric material to a small-diameter wire is difficult. In the present study, we paid attention to the hydrothermal synthesis method, which is one of the piezoelectric material deposition methods. With this method, a minute shape PZT polycrystalline film deposits on a titanium surface immersed in an aqueous solution; therefore, PZT polycrystalline film can be deposited on minute shape titanium. Consequently, there is no need for the piezoelectric materials to adhere to the backing material as conventionally required. Furthermore, the reported material characteristics of PZT polycrystalline film obtained by this method include wideband characteristics at both transmission and receiving frequencies[4-10]. Therefore, it is believed that a wideband small ultrasound probe with a PZT polycrystalline film obtained by such method can be made with less difficulty.

In the present study, we fabricated a small ultrasound probe with a transducer diameter of 0.6 mm for trial, evaluated the frequency characteristics of its transmission and receiving sensitivities under water, conducted ultrasound transmission and receiving experiments, and evaluated its distance resolution using a test piece. This report deals with the results obtained.

II. ASSEMBLY OF THE SMALL ULTRASOUND PROBE

As the transducer of the small ultrasound probe, we used a titanium wire of 0.6 mm in diameter and 40 mm in length, with a PZT polycrystalline film deposited by the hydrothermal synthesis method on its end face. The film thickness was set to be 20 μm in order to have resonance frequencies of λ/4 and λ/2 at 25 MHz and 50 MHz, respectively. Figure 1 shows the scanning electron microscope (SEM) image of PZT polycrystalline film surface. After film formation, the film thickness was confirmed to be about 20 μm. Figure 2 shows the structure of the small ultrasound probe. The structure was designed so that the ground side electrode enclosed all hot side electrodes to improve the S/N ratio. In the already reported structure[4], since the gold electrode section was thin, the wiring resistance across electrodes on the PZT film and GND of the BNC connector was as high as several ohms (Ω) and the electrodes at the edge fell apart during use. In the present structure, conductivity was improved and protection was provided for the edge part by an electrically conductive adhesive applied after deposition of the gold electrode. In doing so, the wiring resistance across the electrode on the PZT film and GND of the BNC connector became 0.5 Ω.
Fig. 1 SEM photographs of hydrothermally deposited polycrystalline film; (a) titanium wire end and (b) cross section.

Fig. 2 Schematic diagram of small ultrasound probe.

III. FREQUENCY CHARACTERISTICS OF TRANSMITTING SENSITIVITY

Frequency characteristic of the transmission sensibility was measured as an evaluation of a small ultrasonic probe; Fig. 3 shows the system used in that measurement. The small ultrasound probe trial with an effective element diameter of \( \phi \) 0.6 mm was used as the acoustic source. A hydrophone [ONDA: HNV-0200] with an effective element diameter of \( \phi \) 0.2 mm calibrated between 5 and 60 MHz was used as receiver. The input signal was 20 cycles of burst sine wave, with a cycle period of 40 ms. The distance between the acoustic source and the hydrophone was set at 7 mm. Measurements were taken at 100 kHz intervals from 5 to 60 MHz. Figure 4 shows the results. The frequency characteristics of transmitting sensitivity of this small ultrasound probe were confirmed to be \( \lambda/4 \) resonance and \( \lambda/2 \) peak around 25 MHz and 50 MHz. Moreover, the transmission of the ultrasonic wave was able to be confirmed in 100 MHz.

IV. FREQUENCY CHARACTERISTICS OF RECEIVING SENSITIVITY

The receiving sensitivity of the small ultrasound probe was calibrated by comparison calibration method using a hydrophone calibrated for sensitivity. Figure 5 shows the system used to measure the frequency characteristics of receiving sensitivity. Two prototype small ultrasound probes were used for the measurement. One was used for the sound source, and another one was used for the receiver of the comparison calibration. A hydrophone made of PVDF [ONDA: HNV-0200] with an effective element diameter of 0.2 mm calibrated between 1 and 60 MHz and the small ultrasound probe were used as receivers. Frequency characteristics of receiving sensitivity was measured by comparing this hydrophone made of PDVF with the prototype small ultrasound probe. The input signal was a sine-wave burst, rippling 20-waves with a cycle period of 40 ms. Measurements were taken at 100 kHz intervals from 5 to 60 MHz. The distance between the acoustic source and the hydrophone was set at 7 mm.

The measurement results are shown in Fig. 6. This figure indicates that the frequency characteristics of receiving sensitivity of this small ultrasound probe was ± 18.2 dB around – 254.8 dB in the range of 1 to 60 MHz. At 20 MHz and above, frequency characteristics were flat as compared with those obtained with the PVDF hydrophone.
V. TRANSMITTING AND RECEIVING CHARACTERISTICS OF ULTRASOUND PROBE

Figure 7 shows the system used to measure transmitting and receiving characteristics of ultrasound. The small ultrasound probe was immersed in water and a reflector made of stainless steel was placed at a point 5 mm apart from its acoustic radiation plane. A pulser receiver [Panametrics-NDT: Model 5900PR] was used for transmission and receiving from the ultrasound probe. Figure 8 shows a signal transmitted from the pulser receiver. Figure 9 shows a frequency spectrum of Fig. 8. The received signal was 54 dB amplified by a preamplifier provided in the pulser-receiver to confirm the receiving voltage waveform.

Figure 10 shows the receiving voltage waveform resulting from ultrasound transmitting and receiving experiments using the small ultrasound probe in the water. A receiving waveform was confirmed 7.5 μs after the transmission. The distance resolution calculated from the receiving waveform in Fig. 10 was 32 μm. Figure 11 shows the frequency spectrum shown in Fig. 10. The fractional bandwidth was calculated from Fig. 11 to be 99% and the central frequency to be 50 MHz, which confirmed the wideband characteristics of the probe. Table 1 shows the calculation results. The pulse width and distance resolution were calculated in a range from the maximum receiving voltage to −20 dB, and the fractional bandwidth was calculated in a range from the maximum amplitude of the power spectrum to −6 dB.
VI. MEASUREMENT OF THE DISTANCE RESOLUTION

In order to measure the actual distance resolution calculated in Table 1, a test piece with steps in a staircase pattern was produced. Figure 12 shows the cross-sectional view of the test piece. The test piece was a glass substrate of 500 \( \mu \text{m} \) in thickness with 7-steps that ranged between 5 and 35 \( \mu \text{m} \) at 5 \( \mu \text{m} \) intervals in depth. The interval in the lateral direction was set at 600 \( \mu \text{m} \), which was identical to the diameter of the small ultrasound probe. Scanning was performed using a similar device for the test piece as that used for the transmitting and receiving experiments, while transmitting and receiving ultrasound signals and a B-mode image of the test piece was photographed. It scanned at intervals of 10 \( \mu \text{m} \). Figure 13 shows the result obtained. It was confirmed that steps of 20 \( \mu \text{m} \) were discriminated while steps of 15 \( \mu \text{m} \) and below were not. The resolution was more than 32.2 \( \mu \text{m} \) based on the distance resolution calculated from the receiving waveform.

Table 1: Characteristics of a small ultrasound probe.

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance resolution [( \mu \text{m} )]</td>
<td>32</td>
</tr>
<tr>
<td>Upper frequency [MHz]</td>
<td>25</td>
</tr>
<tr>
<td>Lower frequency [MHz]</td>
<td>74</td>
</tr>
<tr>
<td>Center frequency [MHz]</td>
<td>50</td>
</tr>
<tr>
<td>Fractional band width [%]</td>
<td>99</td>
</tr>
</tbody>
</table>
Fig. 13 B-mode image of distance resolution test piece.

VII. SUMMARY

Using a PZT polycrystalline film obtained by the hydrothermal synthesis method on the end face of a titanium wire, a small ultrasound probe with a transducer diameter of 0.6 mm was experimentally fabricated. Measurements of frequency characteristics of transmitting sensitivity and receiving sensitivity in water revealed ± 22.7 dB around 165.5 dB at transmission with frequencies from 1 MHz to 60 MHz. At receiving, ± 26.4 dB was obtained around – 252.2 dB.

Transmitting and receiving of ultrasound signals were confirmed in water using the small ultrasound probe. Its distance resolution was 32 μm in the range of – 20 dB and its fractional bandwidth was 99% in the range of – 6 dB, indicating wideband frequency characteristics for this probe without matching layer.

A test piece was produced to measure distance resolution confirming that at depths of 20 μm the steps could be discriminated. In the future, we intend to calibrate sensitivity at higher frequencies by mutual calibration and to promote miniaturization of the probe.

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REFERENCES