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ORIGINAL ARTICLE

Transmission of 100-MHz-range ultrasound through a fused quartz fiber

Takasuke Irie · Norio Tagawa · Masayuki Tanabe · Tadashi Moriya · Masasumi Yoshizawa · Takashi Iijima · Kouichi Itoh · Taku Yokoyama · Hideki Kumagai · Nobuyuki Taniguchi

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Abstract

Purpose This paper describes an investigation into direct observation of microscopic images of tissue using a thin acoustic wave guide.

Methods First, the characteristics of the ultrasonic wave propagated in a fused quartz fiber were measured using the reflection method in order to study the insertion loss and the frequency shift of the ultrasonic wave transmitted from the transducer. Next, a receiving transducer was placed close to the end of the fiber, and the characteristics of the ultrasonic waves propagated through the acoustic coupling medium were measured using the penetration method in order to study the insertion loss and the frequency-dependent attenuation of the penetrated waves. Finally, a C-mode image was obtained by optimizing the measuring conditions using the results of the above measurements and scanning the ultrasonic beams on a target (coin) in water.

Results A reflected wave with a peak frequency of approximately 220 MHz was obtained from the end of the fiber. The transmitted ultrasonic waves propagated through the acoustic coupling medium were detected with a frequency range of approximately 125–170 MHz, and the maximum detectable distance of the waves was approximately 1.2 mm within the 100-MHz frequency range. Finally, a high-frequency C-mode image of a coin in water was obtained using a tapered fused quartz fiber.

Conclusion The results suggest that it is necessary to improve the signal-to-noise ratio and reduce the insertion loss in the experimental system in order to make it possible to obtain microscopic images of tissue.

T. Irie (✉) · N. Tagawa · M. Tanabe
Graduate School of System Design, Tokyo Metropolitan University, 6-6 Asahigaoka, Hino, Tokyo 191-0065, Japan
e-mail: irie@microsonic.co.jp

T. Irie
Research and Development, Microsonic Co., Ltd, Tokyo, Japan

T. Moriya
Professor Emeritus of Tokyo Metropolitan University, Hino, Tokyo, Japan

M. Yoshizawa
Monozukukuri Department, Metropolitan College of Industrial Technology, Tokyo, Japan

T. Iijima
Research Center for Hydrogen Industrial Use and Storage, National Institute of Advanced Industrial Science and Technology, Tsukuba, Ibaraki, Japan

K. Itoh
Department of Internal Medicine, Hitachi-Omiya Saiseikai Hospital, Hitachiomiya, Ibaraki, Japan

T. Yokoyama
Department of Surgery, Hitachi-Omiya Saiseikai Hospital, Hitachiomiya, Ibaraki, Japan

H. Kumagai
Department of Pediatrics, Hitachi-Omiya Saiseikai Hospital, Hitachiomiya, Ibaraki, Japan

N. Taniguchi
Department of Clinical Laboratory, Jichi Medical University, Shimotsuke, Tochigi, Japan

Keywords High-frequency ultrasonic wave · Microscopic image · Tapered fused quartz fiber · Needle-type ultrasonic probe

Introduction

In current pathological examinations, expensive testing using computed tomography and magnetic resonance imaging is required before establishing whether tissue is malignant or benign. Furthermore, tissue diagnosis currently takes time, because it requires a tissue sample obtained by biopsy and observation using an optical microscope, and therefore places a burden on the patient. The main objective of the present study is to enable an operator to directly obtain microscopic images of tissue without removing a tissue sample from a patient. In order to establish this objective, we have been developing a needle-type ultrasonic probe that uses a thin fiber [1–3]. The diameter of the probe is so small that it can be inserted into body tissue without placing a severe burden on the patient and still retain non-invasiveness. Previously, it was reported that a fused quartz fiber was used as the guide line using the L(0,1) and L(0,3) modes of the Pochhammer–Chree wave in the 20-MHz range [4–8]. We also reported that the ultrasonic pulse wave generated by a 50-MHz transducer with a focal length of 10 mm was transmitted in a fiber 125 μm in diameter and reflected at the end face [9]. To obtain a high resolution of the order of 10 μm, however, it is necessary to use an ultrasonic wave with a frequency higher than 100 MHz. We therefore carried out an experiment on the transmission of high-frequency ultrasonic waves through a fused quartz fiber using a 220-MHz transducer. High-frequency ultrasonic waves over 100 MHz were transmitted into a fused quartz fiber and reflected at the end face. Moreover, the echoes from a reflector through the acoustic coupling medium were detected using a tapered fused quartz fiber. However, it was difficult to investigate the characteristics inside the fiber. To solve this problem, we conducted an experiment using the finite element method (FEM) simulator PZFlex and tried to detect the echoes from the reflector using a tapered fused quartz fiber with a large aperture at the end face [10]. In this paper, we describe the experimental results of measurement of the characteristics of 100-MHz-range ultrasonic waves in the acoustic coupling medium through the fiber and the imaging of a coin in water using a tapered fused quartz fiber.

Needle-type ultrasonic probe

In order to use a thin fiber as an ultrasonic probe, it is necessary to find the propagation characteristics and the insertion loss of the high-frequency ultrasonic wave in the fiber and the acoustic coupling medium. We used the needle-type ultrasonic probe shown in Fig. 1a. The T_X/R_X transducer was composed of the transducer (PZT) and the delay material. In order to transmit a high level of ultrasonic energy efficiently from the transducer to the fiber, we attached the transducer to the large surface side of the fiber, as shown in Fig. 1. Both ends of the fiber were polished, as shown in Fig. 2. Ultrasonic gel was used as the acoustic coupling medium between the fiber and the transducers.

When an electric pulse (V_A) is applied to the transducer (PZT), an ultrasonic wave is generated and propagated to the tapered fused quartz fiber via the delay material. The ultrasonic wave reflected at the end (B) of the delay material of the transducer and that reflected at the end of the fiber (C) are propagated back to the transducer and converted into electric signals (V_B and V_C). Typical waveforms of V_B and V_C corresponding to the end of the delayed materials and the end of the fiber are shown in Fig. 1b.

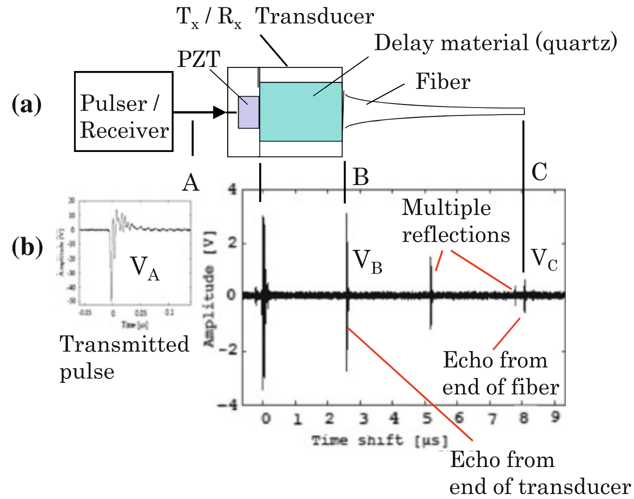


Fig. 1 Needle-type ultrasonic probe

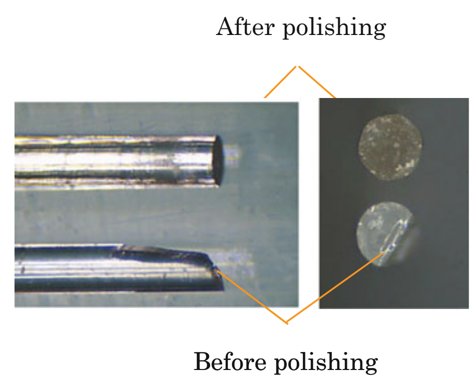


Fig. 2 Polishing the end of the fiber

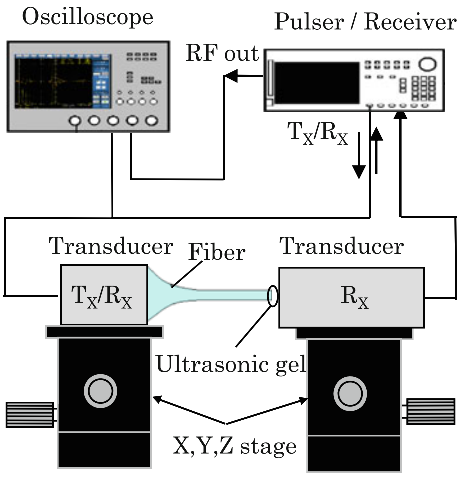


Fig. 3 Block diagram for measurement of propagation characteristics in the fiber

Measurement of propagation characteristics and insertion loss of the fiber by the reflection method

Experimental system

Figure 3 shows a block diagram of measurement using the reflection method and the penetration method. The needle-type ultrasonic probe was connected to a common transducer connector of the pulser/receiver (Fig. 3). The system consisted of a pulser/receiver (Panametrics model 5900PR: selectable mode of reflection and transmission, selectable gain of 26–54 dB, and selectable attenuation of 10–65.5 dB in the receiver), a transmitting/receiving transducer (T_X/R_X transducer: Panametrics V2113, PZT, 3 mm diameter, 220 MHz center frequency, 95–278 MHz frequency range), a receiving transducer (R_x transducer: Panametrics V3878, PZT, 2 mm diameter, 170 MHz center frequency, 100–220 MHz frequency range), a tapered fused quartz fiber (16.7 mm length, 3.2 mm diameter of the large surface side, 0.6 mm diameter of the small surface side), and an oscilloscope (Tektronix TDS5104B).

Measurements

For measurement of the amplitude of signals, the value of the gain of the receiver was set to 40 dB, and the value of the attenuation was adjusted depending on the size of the signals. We measured the amplitude and frequency of the transmitting pulse (at A in Fig. 1), the echo reflected from the end of the transducer (at B in Fig. 1), and the echo reflected from the end of the fiber (at C in Fig. 1). Then, removing the fiber from the T_X/R_X transducer, the echo reflected from the end of the transducer (at B) was measured ($V_{B'}$). We defined the insertion losses of the reflected signals (V_B, V_C, and $V_{B'}$) as $IL_{(B)} = 20\log(V_B/V_A)$, $IL_{(C)} = 20\log(V_C/V_A)$, and $IL_{(B)'} = 20\log(V_{B'}/V_A)$, respectively.

Results

Figure 4 shows the waveforms and frequency spectra of the RF echo signals measured at A, B, and C. As shown in Fig. 4a, the amplitude and peak frequencies of the observed transmitting pulse at A were approximately 65 $V_{P–P}$, 140 MHz, and 180 MHz, respectively. At B, they were approximately 6.0 $V_{P–P}$, 120 MHz, and 200–220 MHz with an attenuation value of −24 dB, as shown in Fig. 4b. At C, they were approximately 1.6 $V_{P–P}$, 130 MHz, and 200–220 MHz with an attenuation value of −20 dB, as shown in Fig. 4c. Finally, for the wave with the fiber removed, they were approximately 6.5 $V_{P–P}$, 130 MHz, and 180–220 MHz at B with an attenuation value of −24 dB, as shown in Fig. 4d. Based on the measurements, the insertion losses $IL_{(B)}$, $IL_{(C)}$, and $IL_{(B)'}$ were as follows:

$IL_{(B)} = 20\log(1.0/65) \rightarrow$ approximately −35 dB (because the gain and attenuation were set at 40 and −24 dB, respectively)

$IL_{(C)} = 20\log(0.16/65) \rightarrow$ approximately −52 dB (because the gain and attenuation were set at 40 and −20 dB, respectively)

$IL_{(B)'} = 20\log(1.1/65) \rightarrow$ approximately −34 dB (because the gain and attenuation were set at 40 and −24 dB, respectively).

Measurement of acoustic insertion loss of the needle-type ultrasonic probe by the transmission method

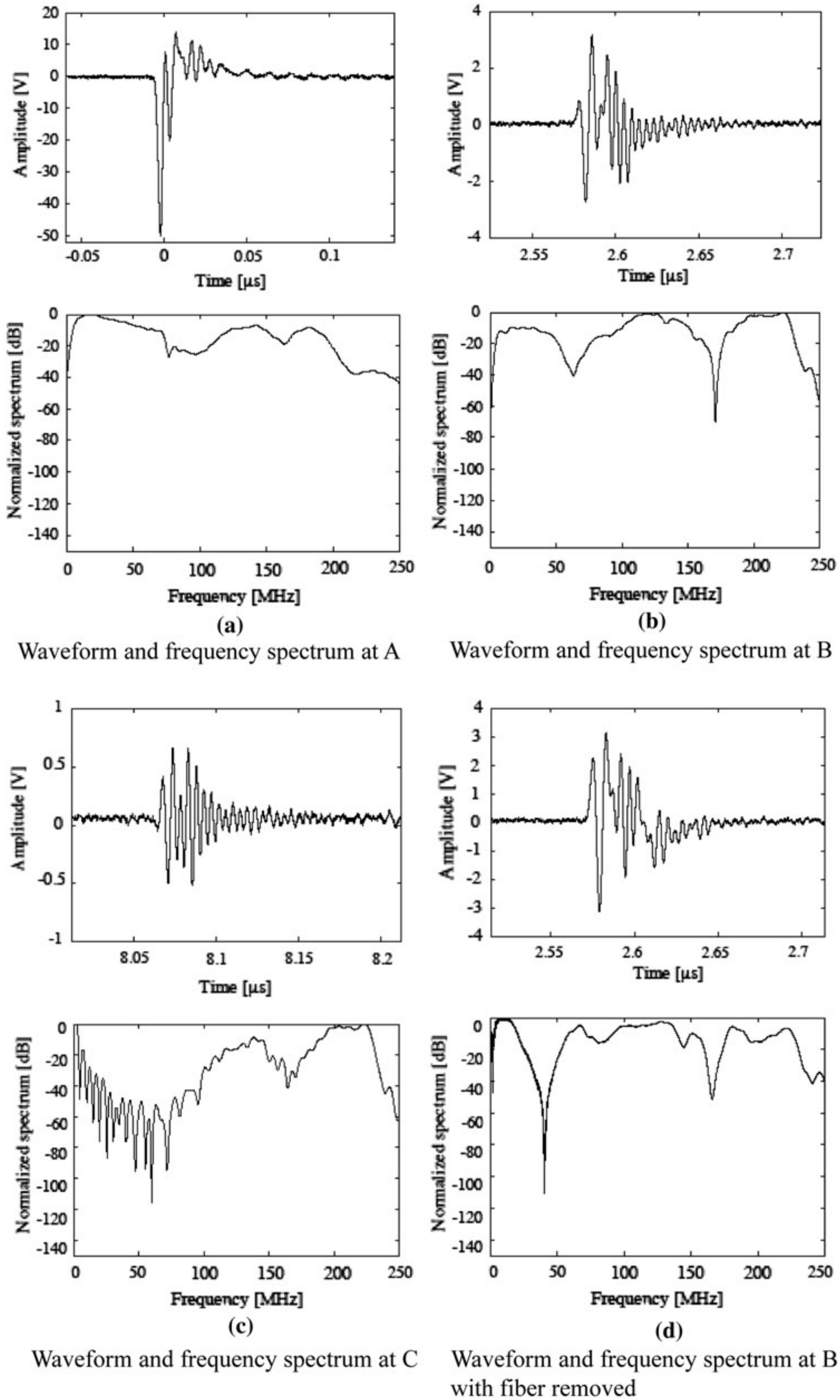
Measurements

We defined the acoustic insertion loss using Fig. 5a, b. Two transducers were in contact with each other at the flat surfaces of the delay materials, as shown in Fig. 5a. When one transducer was applied, an electric pulse, the generated ultrasonic wave, was propagated through the delay materials and detected by the other transducer. Figure 5b shows the tapered fused quartz fiber inserted between the flat ends of the delay materials. When one transducer was excited, the generated ultrasonic wave was propagated and detected by the other transducer.

Results

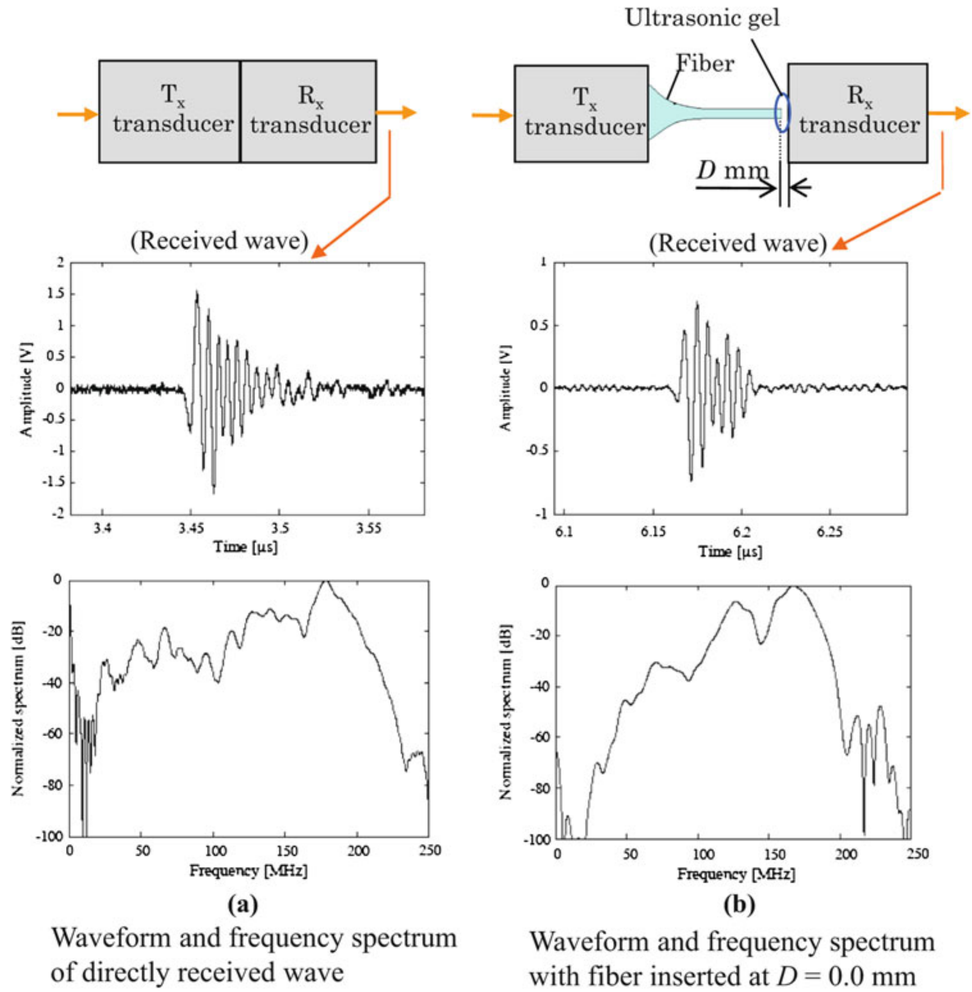
In Fig. 5a, the amplitude (V_0) and frequency of the ultrasonic wave of the received signals were approximately 3.3 $V_{P–P}$ and 180 MHz, respectively. In Fig. 5b, on the other

Fig. 4 Waveforms and frequency spectra of waves reflected through the fiber



hand, the amplitude (V_f) and frequency of the received wave were approximately 1.4 $V_{P\text{–}P}$ and 170 MHz, respectively. We confirmed that the amplitude of the reflected signal from the flat surface was small compared with the transmitted signal. Therefore, the acoustic insertion loss $IL_{(f)}$ was calculated as follows:

Fig. 5 Block diagram for measurement of propagation characteristics in the acoustic coupling medium



$IL_{(f)} = 20\log(V_f/V_0) = 20\log(1.4/3.3) \rightarrow$ approximately -8 dB.

Measurement of propagation characteristics in the acoustic coupling medium by the transmission method

In order to estimate the characteristics of a tissue, it is necessary to find the propagation characteristics of the ultrasonic wave in the acoustic coupling medium (ultrasonic gel) that has almost the same acoustic impedance as the tissue and the insertion loss of the high-frequency ultrasonic wave in the experimental system. Therefore, we measured the amplitude and the frequency of the ultrasonic wave transmitted into the ultrasonic gel at each distance when the receiving transducer was moved far from the end of the fiber.

Measurements

The values of gain and attenuation of the receiver were set at 40 and 20 dB, respectively. First, the amplitude and frequency spectrum of the ultrasonic wave propagated through the fiber were measured when the end of the fiber was attached to the receiving transducer. Next, by moving the receiving transducer far from the end of the fiber, the frequency and amplitude of the ultrasonic waves that penetrated through the ultrasonic gel were measured at intervals of 0.2 mm. The distance between the fiber and the receiving transducer was D mm, as shown in Fig. 5 (b).

Results

Figure 6 shows the amplitudes and frequency spectra of the high-frequency ultrasonic waves propagated in the ultrasonic gel as a function of distance when the receiving transducer was moved far from the end of fiber at intervals of 0.2 mm. When the distance D was 0.0 mm, the amplitude and peak frequency were approximately 1.4 $V_{P\text{–}P}$ and 170 MHz, respectively. When the distance D was 0.4 mm, the amplitude and peak frequency were approximately 0.9 $V_{P\text{–}P}$ and 165 MHz, respectively, and when the distance D was 1.0 mm, the amplitude and peak frequency were approximately 0.4 $V_{P\text{–}P}$ and 125 MHz, respectively. The

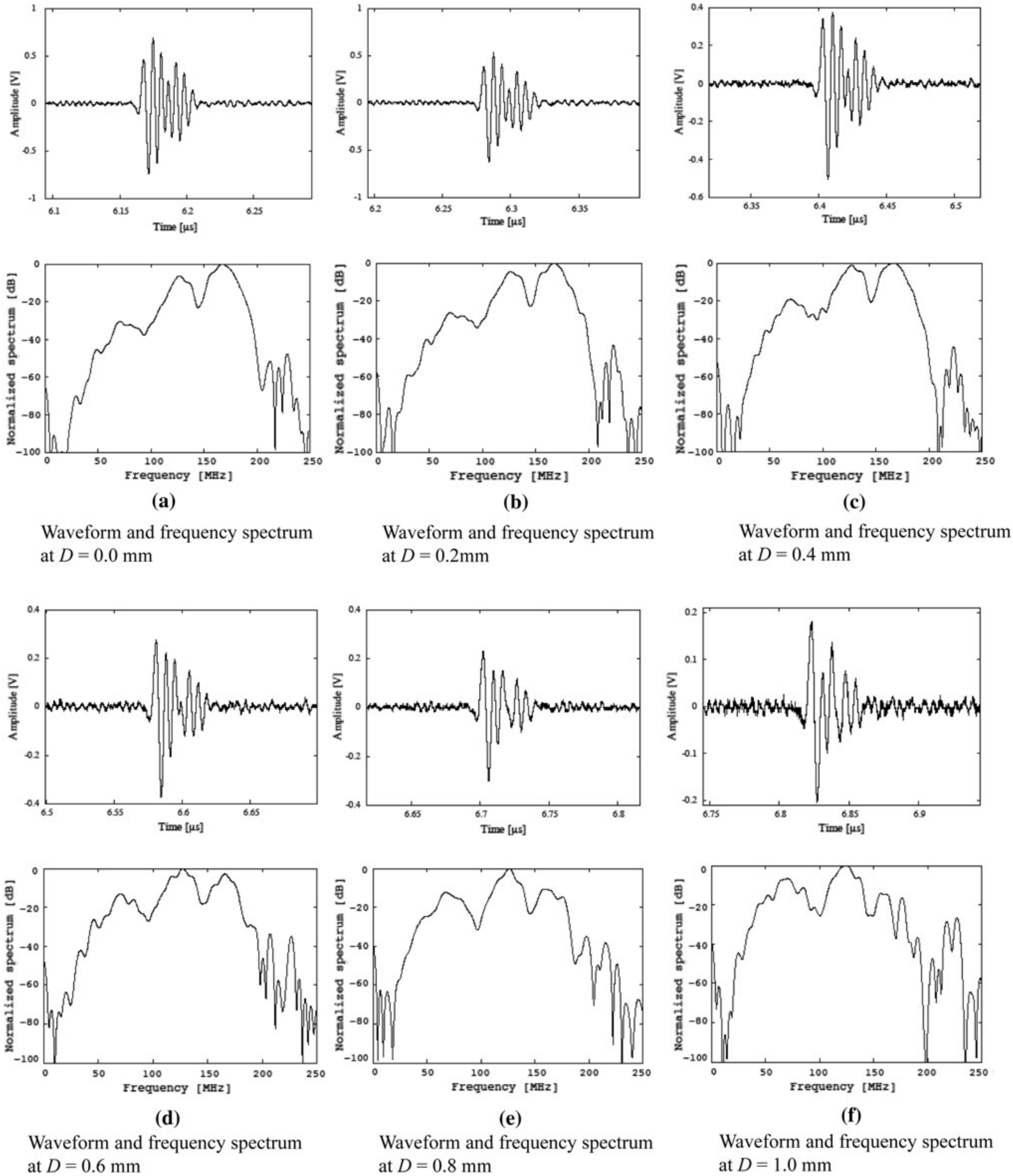
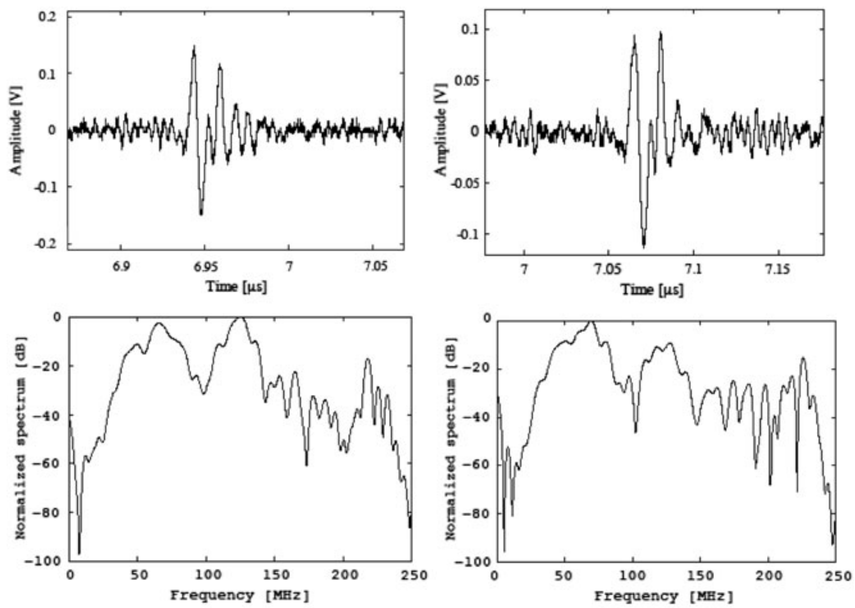


Fig. 6 Propagation characteristics of ultrasonic waves in the ultrasonic gel

results of these measurements are shown in Fig. 7. Based on the measurements, the frequency-dependent attenuation in the acoustic coupling medium was calculated by two slopes of lines (the dotted line A and B) in the frequency range of 165–175 and 125 MHz, respectively. If we define the attenuation constant for the medium by the slope of the curve, its range is 0.08–0.09 dB/(mm MHz).



(g) Waveform and frequency spectrum at $D = 1.2$ mm

(h) Waveform and frequency spectrum at $D = 1.4$ mm

Fig. 6 continued

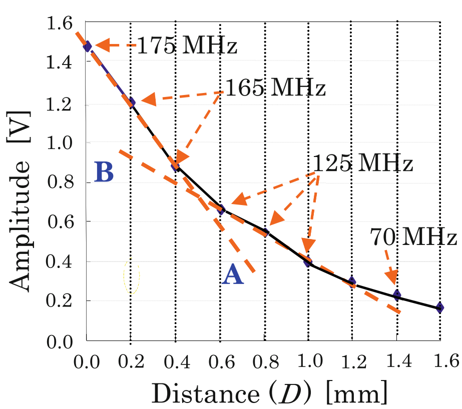


Fig. 7 Frequency-dependent attenuation of ultrasonic waves through the ultrasonic gel

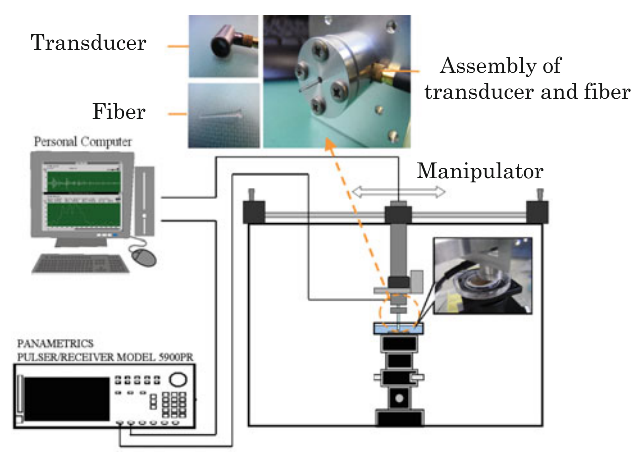


Fig. 8 Block diagram of C-mode imaging system

Imaging of a coin using the reflection method

We obtained a C-mode image using the fabricated system.

Materials and experimental system

Figure 8 shows a block diagram of the C-mode imaging system. The system consisted of a pulser/receiver, a transducer, a fiber, a manipulator, and a personal computer with an analog/digital (8 bit) converter. The pulser/receiver, the transmitting transducer, and the fiber were the same as those used in the measurement of reflected waves from the end of the fiber (Fig. 1). A coin that was the target of the imaging was placed in water. The ultrasonic waves radiated from the transducer were transmitted into the water through the fiber. The echoes reflected from the coin were received by the transducer through the fiber and sent to the personal computer. The magnitude of the echoes was displayed as brightness on the screen. The measurements were performed extending over the coin using a manipulator controlled by a stepping motor. The moving interval of the transducer, i.e., the scanning interval of the

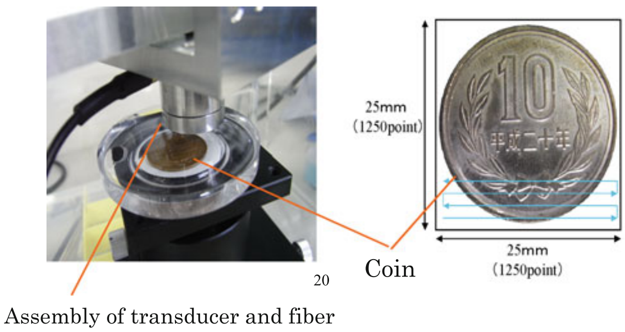


Fig. 9 Scanning method for obtaining C-mode image of a coin

Fig. 10 C-mode image of the coin

ultrasonic beams, was at least 20 µm. The entire scanning widths in the X and Y directions were 25 and 25 mm, as shown in Fig. 9b.

Results

As shown in Fig. 10, a C-mode image of the coin was obtained. The echo from the coin was detected; its frequency spectrum is shown in Fig. 11.

Discussion

Ultrasonic (radiation) energy can be expressed by $W = (P^2 \cdot S)/(\rho \cdot c)$, where P is the acoustic pressure, S is the area of the aperture of the transducer, ρ is the density of the medium, and c is the propagation velocity. Therefore, to transmit a high level of ultrasonic energy into the fiber, the use of a large-diameter transducer is required. When a needle-type ultrasonograph is used, a small transducer, which is preferably less than 1 mm in diameter, is used to avoid causing the patient unnecessary pain.We therefore used a tapered quartz fiber with a large end face in this

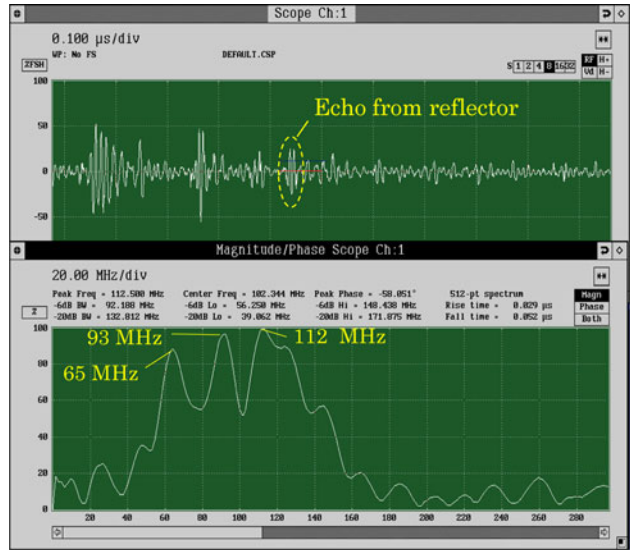


Fig. 11 Echo from the coin and the frequency spectrum

experiment. The propagation characteristics of the ultrasonic wave in the quartz fiber are well known as Pochhammer–Chree waves [11]. When the $\omega \cdot a$ value, where ω is its angular frequency and a is the radius of the fiber, is small, single modes such as L(0, 1)–L(0, 3) are useful [12]. In this study, however, we found that the high-frequency ultrasonic waves (from approximately 130 to 220 MHz) propagated in the region of large $\omega \cdot a$ value, where there exist many modes. Based on the results of the experiment, it is estimated that the lower bound of the $\omega \cdot a$ value is approximately 2.45×10^5 rad m/s. The experimental results show that the ultrasonic pulse was transmitted in the tapered fused quartz fiber, which means that the pulse was transmitted by multiple modes, as is the case with optical fiber communication.

According to measurements of the propagation characteristics and the insertion loss of the fiber using the reflection mode, it was found that the ultrasonic waves with a high frequency (200–220 MHz) range propagated in the tapered quartz fiber, as shown in Fig. 4c. The insertion loss of the reflected signals from the end of the fiber was approximately −52 dB in the round-trip measurement. This seems to be large, but it includes the insertion loss of the transducer in the round-trip measurement. The insertion loss of the fiber itself was approximately (35–52) dB = −17 dB in the round-trip measurement. According to the single-trip measurement, it was calculated to be approximately 8.5 dB. As the insertion loss of the transducer after removing the fiber from the transducer was almost the same as that before, it may be said that the insertion loss of the fiber itself was approximately −17 dB in the round-trip measurement.

According to measurements of propagation characteristics in the acoustic coupling medium, the acoustic insertion loss was approximately −8 dB for the single-trip measurement. This is almost the same as the result obtained in the reflection mode. Therefore, it is surmised that the insertion loss of the fiber itself is approximately −8 dB in the single-trip measurement. In the case of measurement of the propagation characteristics in the acoustic coupling medium, if we could define the attenuation constant for the acoustic coupling medium by the slope of the curves obtained in this measurement, it would be 0.08–0.09 dB/(mm MHz). This value is smaller than that of tissue [approximately 0.3 dB/(mm MHz)]. Therefore, it is necessary to improve the sensitivity and signal-to-noise ratio of the experimental system. In this measurement, it is surmised that the setting of the tools (the fiber and the receiving transducer) was not closely optimized. For example, the direction of the ultrasonic beam radiated from the fiber should be kept at a right angle to an observing object.

Regarding the imaging of a coin, it was difficult to obtain a C-mode image at a high resolution due to the fact that the energy of the ultrasonic wave reflected from the target was not very large. The direction of the ultrasonic beam radiated from the fiber must be kept at a right angle to the surface of the reflector (coin), and the reflector should be directed toward the point of maximum energy of the ultrasonic beam. By adjusting the direction, an image of the coin was obtained with a higher resolution, as shown in Fig. 10. It seems that the measurement conditions described in these two cases were optimized. The frequency spectrum of an echo reflected from the coin is shown in Fig. 11. It has three peak frequencies, 65, 93, and 112 MHz, and their wavelengths are approximately 14, 17, and 24 μm, respectively. Therefore, the image quality of the C-mode image obtained in the system may be changed under various conditions. Under the present condition, since the ultrasonic beam was not focused in the lateral direction, the resolution depended on the diameter of the fiber, which was approximately 0.6 mm. In this experiment, the resolution of the C-mode image was considered to be greater than 24 μm in the axial direction and 600 μm in the lateral direction. The main objective of the study was to obtain a tissue image; however, this was difficult because the echo from it was so much weaker than that of the copper (Cu) coin. The intensity of the reflection from a target depends on the acoustic characteristic impedance (Z) of the target; that is, the intensity of the reflection from a target placed in water [with an impedance of 1.49 (kg/m^2 s)] increases when the target impedance is large. The impedance of Cu is 44.6 kg/(m^2 s). On the other hand, the impedance of tissue is approximately 1.38 kg/(m^2 s) (muscle) and −7.8 kg/(m^2 s) (cranial bone). Therefore, it is necessary to reduce propagation loss and improve signal-to-noise ratio in the experimental system.

Conclusions

We obtained a high-frequency C-mode image of a coin in water using a tapered quartz fiber. The frequency bandwidth of a reflected signal in the image was approximately 65–110 MHz. As the wavelength at a frequency of 110 MHz is approximately 12 μm, it seems that a microscopic image of the coin with axial resolution of tens of micrometers was obtained. However, it is not enough to be called a microscopic image in the lateral resolution because the lateral resolution depends on the size of the ultrasound beam radiated from the fiber, i.e., the size of the ultrasound beam is related to the diameter (0.6 mm) of the fiber. We will improve the lateral resolution by focusing the ultrasound beam and reducing the size of the fiber as far as possible. We will also try to obtain an image of tissue (e.g. cranial bone) with high acoustic impedance by improving the signal-to-noise ratio and reducing the propagation loss of the experimental system.

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