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Ultrasound-Modulated Optical Tomography Using Optical Axis Scanning and Pulse-Delay Scanning

光軸走査と光パルス遅延走査による
超音波変調光トモグラフィー

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1. Introduction

In the fields of medical engineering and food engineering, there is a growing interest in obtaining optical properties inside objects non-invasively. It is challenging to measure deep within a scattering medium with high resolution because the light is diffused by the scattering medium. Diffuse optical tomography is a typical technique for imaging the scattering and absorption coefficients, and time-resolved measurements are generally used for higher accuracy[1, 2)]. However, picosecond pulsed lasers are required for time-resolved measurements, which makes the equipment expensive. Therefore, ultrasound-modulated optical tomography (UOT) has been proposed as a method for high-resolution measurement in the scattering medium with a continuous light source. Light interacts with ultrasound in the scattering medium[3, 4)]. This phenomenon can be used to obtain the optical characteristics of a specific region in a scattering medium by tagging the light and demodulating it with a detector. It is possible to image deep in the body with high resolution, because ultrasound is less scattered in the body. However, UOT requires mechanical scanning of the position of the transducer to obtain a spatial distribution. It is a factor that complicates the measurement system. In this paper, we propose a method to obtain the distribution of optical characteristics along the ultrasound propagation direction without changing the relative position of the ultrasonic transducer and the phantom by controlling the timing of the laser pulses to the ultrasound burst. Phantoms made of agar were imaged in the direction of ultrasound propagation using beam-type ultrasound transducer.

2. Principle of Measurement

Modulation of the light in the optical scattering medium by the ultrasound is caused by two phenomena: 1) a change in the light scattering path and a change in the optical path length due to the movement of particles by ultrasound, and 2) a change in the refractive index of medium due to a change in the density of medium. The change in optical path length causes phase modulation, and the light with the angular frequency of ω_{opt} is modulated to that with the angular frequency $\omega_{opt}+\omega_a$, if it passes through the area irradiated with ultrasound at angular frequency of ω_a. This modulated light can be detected by calculating the contrast of the speckle image. The contrast of a speckle image can be expressed as the ratio of the standard deviation to the ensemble average of the image, as

$$C_{on}=\frac{\langle (I(x,y)-\langle I(x,y)\rangle)^2\rangle^{\frac{1}{2}}}{\langle I(x,y)\rangle} \approx \frac{\left(\langle I_{um}{}^2\rangle-\langle I_{um}\rangle^2\right)^{\frac{1}{2}}}{\langle I_{um}\rangle(1+\langle I_m\rangle/\langle I_{um}\rangle)}, \qquad (1)$$

where $I(x,y)$ is light intensity in the image, I_{um} is unmodulated light intensity, I_m is modulated light intensity, and $\langle\ \rangle$ represents ensemble average[3)]. The ratio of ensemble average of unmodulated and modulated light intensity is the modulation depth and can be expressed as

$$M=\frac{\langle I_m\rangle}{\langle I_{um}\rangle}=\frac{C_{off}}{C_{on}}-1\,, \qquad (2)$$

where, C_{off} is the contrast of the case with the ultrasound turned off. A burst signal is emitted from an ultrasonic-transducer and a laser pulse is emitted with a T_d delay. The direction of ultrasound propagation is set to Z, and the light passing through the position where $Z=T_d v_a$ is modulated. v_a is the speed of sound in the medium. At the same time, by setting the position of the optical axis to $Z=T_d v_a$, we can obtain the distribution of optical characteristics along the direction of ultrasound propagation by measuring $M(Z)$ under the same conditions of incident light intensity and positional relationship between the incident and observation positions. A beam-type ultrasonic transducer was used to equalize the acoustic intensity in the Z direction.

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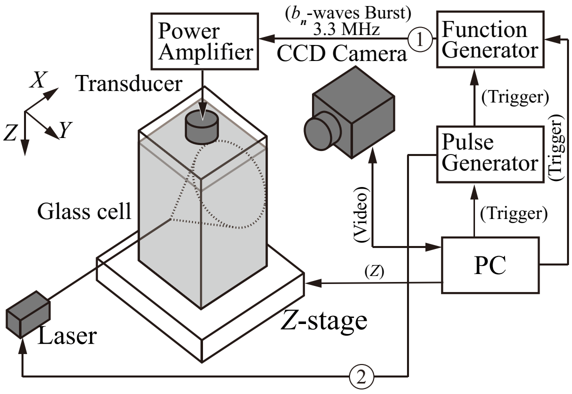

Fig. 1 Schematic diagram of measuring system.

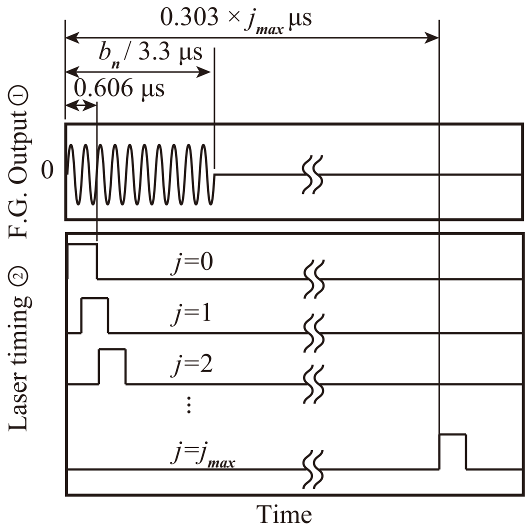

Fig. 2 Output signal from the Function Generator and Laser timing.

2. Experimental setup

The experimental setup is shown in **Fig. 1**. The signals output from the function generator (F. G.) and Laser timing as shown in **Fig. 2**. The function generator outputs a burst signal with a center frequency of 3.3 MHz and a number of waves of b_n in a period of 800 μs. A pulse signal with a pulse width of 0.606 μs is output from the pulse generator $0.303j$ μs after the burst signal is output. The delay of the pulse generator was scanned from $j = 0$ to $j = j_{max}$ for j, and the stage position was scanned so that $0.303jv_a \times 10^{-6} = Z$ with respect to j. The exposure time of the CCD camera was 37000 μs. Agar made of 400 ml of water, 1.6 g of agar powder, and 0.16 ml of milk was used as the phantom. The area about 40 mm below the ultrasonic transducer was colored with cobalt blue.

4. Results and Discussion

Figure 3(a) shows a cross-sectional view of the agar used in the experiments. **Figure 3(b)** shows

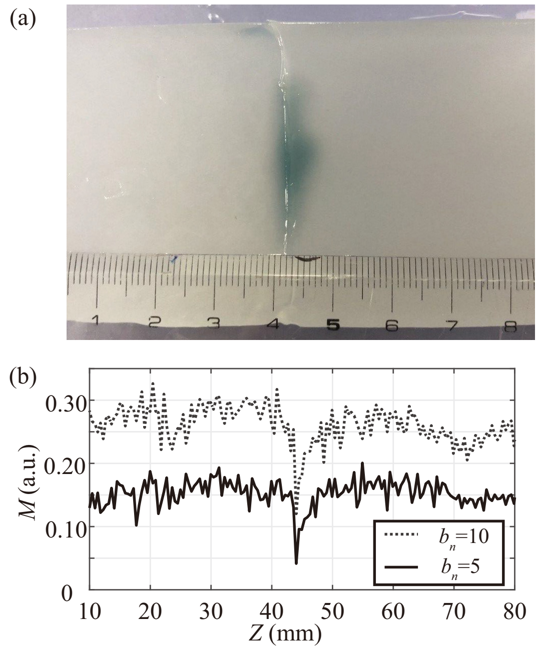

Fig. 3 (a) Cross-sectional view of the phantom, (b) Modulation depth along the Z-axis direction.

the results of the $M(z)$ measurement. Two b_n values of 5 and 10 were used to compare the difference in modulation depth and resolution with the length of the burst signal. The small value of M in the colored area of agar indicates that imaging of the optical characteristics was possible. The resolution of $b_n = 10$ was lower than that of $b_n = 5$, as the range of the decrease in M was wider. As the number of b_n increased, M increased more in the uncolored area relative to the colored area. This enables imaging with high contrast. However, the resolution was reduced. Therefore, it is necessary to determine the bn in consideration of the balance between resolution and contrast.

5. Conclusions

In this paper, we propose a method to obtain the spatial distribution of absorption characteristics by controlling the timing of laser pulses to the ultrasound burst. The spatial distribution of light absorption characteristics of agar in relation to the direction of ultrasound propagation was obtained from the experiments.

References

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