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FEASIBILITY STUDY ON OPTICAL WAVE MICROPHONE USING INCOHERENT LIGHT SOURCE

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Abstract. *The optical wave microphone with no diaphragm, which is based on wave-optics and can detect sound waves by a light beam without disturbing a sound field, is a novel sound measurement technique. As its light source, a laser or coherent light source has been used in the conventional system. In this study, the possibility of LED as a light source for an optical microphone is examined by experiments, demonstrating that LED can be used as a light source and the signal intensity is proportional to sound pressure.*

Keywords: Optical wave microphone, LED, Incoherent light source, Light diffraction method

1. **Introduction.** As a standard technique to measure sound waves, many types of microphones have been developed over the last one hundred years. However, as they use any diaphragm to detect sound waves, they always disturb sound field and cannot respond to high frequency sounds. Therefore, there are always some restrictions on practical applications.

On the other hand, the light diffraction method with no diaphragm is very useful to detect high frequency sound waves in solid or liquid, and has been established in the field of acousto-optics [1]. However, the conventional light diffraction method cannot be applied to audio wave measurements in air, in which the diffracted signal light is extremely weak and also propagates in the penetrating optical beam and cannot be detected by the interference of the latter.

The optical wave microphone is a novel method measuring sounds with very long wavelengths which have not ever been treated in the conventional acousto-optics. In this method, diffraction light generated from optical phase modulation by sound waves is passed through an optical Fourier transform processing and converted into an electric signal by a photodetector. In the fundamental studies, it realized measurements of low-frequency ultrasonic waves [2-5] and acoustic waves [6,7]. Furthermore, in the field of fluid physics or jet noise research, it was applied to mesurement of air flow background noise in jet flow and screech noise exhausted from a nozzle [8,9]. In the acoustic engineering field, it maked it possible to visualize sound field by combining it with the computerized tomography method [10]. In these researches and applications a laser light has been used as a probe light source, because of its coherence.

If a low coherent or incoherent light such as a light emitting diode (LED) or illumination light, which freely exists in our life space can be used for a light source of the optical wave microphone, it can be applied to more various life and engineering fields. Furthermore, if it takes into consideration that sound information is contained in any kind of light such as general light, sunlight and interior illumination light, it can be expected that the LED verification experiment will be a breakthrough to realize a novel method to extract sound information in any general light.

In the present study, experiments to investigate the possibility of sound detection system, in which an LED is adopted as a light source, are carried out, verifying that the sound measurement is possible by the optical wave microphone using an LED light source and the signal intensity is proportional to sound pressure.

The theory of the optical wave microphone is introduced in Section 2, experimental apparatus for this research is shown in Section 3, and an experimental result and consideration to an obtained result is described in Section 4. The last chapter is a conclusion of this study.

2. Principle and Theory.

The fundamental optical setup for theoretical analysis is shown in Figure 1. When an incidence probing laser beam crosses an acoustic wave, diffracted light wave is generated and propagates with and in the penetrating beam through the Fourier optical system and reaches the observing plane, which is set in the back focal plane of a receiving lens. The Doppler-shifted diffraction light is heterodyne-detected there by using the penetrating laser light as a local oscillating power. The spatial intensity distribution of diffraction light signal for the theoretical model shown in Figure 1 is given by the following equation [11,12]:

$$I_{ac}^{(1)} = I_0 \Delta\phi \exp(-u^2) \left[\exp\left\{-(u-\theta)^2\right\} - \exp\left\{-(u+\theta)^2\right\}\right] \cos\omega_a t, \tag{1}$$

where $I_0 = (2P_0/\pi w_f^2)\exp\left[-2(y_f/w_f)^2\right]$: laser power density, $\Delta\phi = k_i(\mu_0 - 1)\Delta d \Delta p/\gamma p$: phase shift, μ_0: refractive index of air, γ: specific heat ratio, Δd: width of sound, p: atmospheric pressure, Δp: sound pressure, k_i: wave number of laser light, ω_a: angular frequency of sound wave, P_0: laser power, $u = x_f/w_f$: the normalized x-coordinate in the back focal plane, $\theta = k_a w_0/2$: the normalized wave number, k_a: wave number of sound wave, w_0: radius of laser beam waist in sound incidence region, w_f, x_f, y_f: radius of the beam cross section, x-coordinate and y-coordinate in the observing plane, respectively.

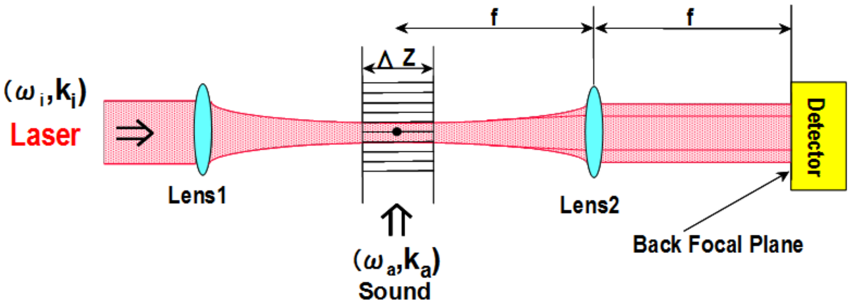
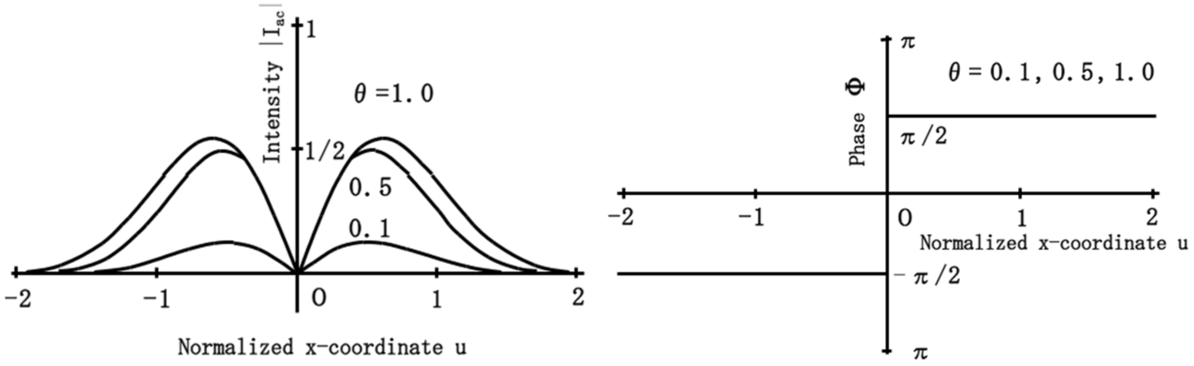


FIGURE 1. Optical setup for theoretical analysis

Examples of theoretical spatial distributions of the intensity and the phase of the diffraction pattern are shown in Figures 2(a) and 2(b), respectively. The spatial profile of diffracted light pattern (I) oscillating at the sound frequency has two peaks on the left and right sides, in which spatial positions almost do not change with frequency in the audio-wave or the low frequency ultrasonic band. On the other hand, the temporal phase difference (Φ) between the left and right diffraction patterns oscillating at ω_a is π, as shown in Figure 2(b). From Equation (1), it is derived that the optical signal intensity is theoretically in proportion to the frequency of sound wave for $\theta \ll 0.8$ and the maximum signal intensity is obtained at $\theta = 0.8$.



(a) Spatial intensity profile (b) Spatial phase profile

Figure 2. Theoretical profiles of diffracted light distribution

3. **Experimental Apparatus.** The abstract of the experimental apparatus is shown in Figure 3. A photograph of the total system is shown in Figure 4. The beam transmission of the probing light is indicated in Figure 5. An LED (wavelength 660 nm; bandwidth (FWHM) 25 nm) of 13 mW is used and the radius of light beam at the intersection point with sound is about 4 mm, which is set by two lenses with $f_1 = 35$ mm and $f_2 = 30$ mm in front of the LED as shown in Figure 3 and Figure 5. The distance between the lenses is 65 mm. When a sound wave crosses the incidence light beam, diffracted light occurs and propagates with or within the penetrating beam and passes through a Fourier optical lens and reaches to a photo detector. In the receiving optics, the focal length of a Fourier transform lens is $f_3 = 35$ mm. The detector is a photodiode of 0.4 mm diameter,

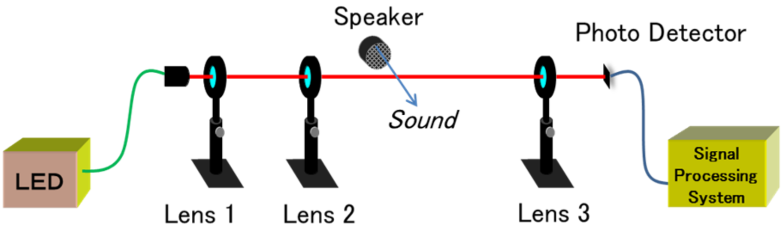


Figure 3. Experimental apparatus

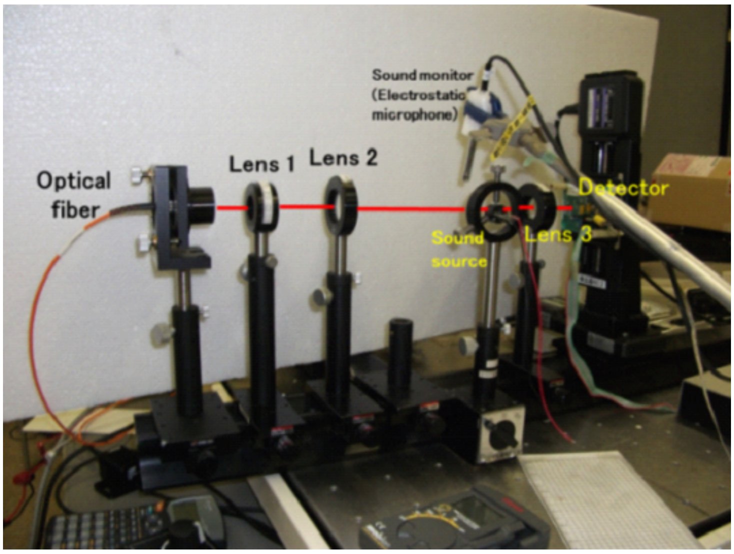


Figure 4. Photograph of experimental apparatus

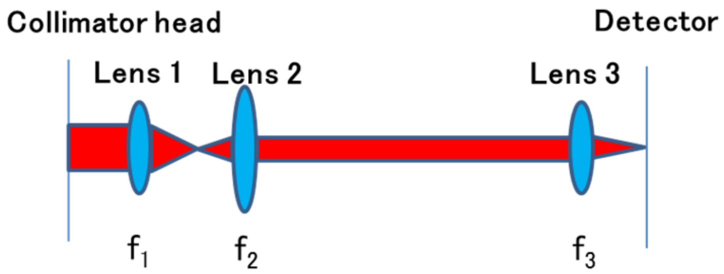


Figure 5. Probing light beam transmission

connected to an electrical detection resistance of 1 kΩ with no bias voltage. The sensitivity is 0.51 A/W (at 760 nm). The output signal from photodiode is amplified, input into and analyzed in a digital oscilloscope with a computer system and a spectrum analyzer. A sound wave of 25 kHz propagates from a transducer of 15 mm diameter. The sound pressure level is monitored by a 1/4 inch electrostatic microphone system.

By using the experimental system mentioned above, the possibility of the optical wave microphone, which uses an LED light source, is examined experimentally. Furthermore, some of the fundamental sound receiving characteristics are measured.

4. **Experimental Result.** It is shown by the theoretical analysis that the spatial profile of diffracted light pattern has two peaks on the left and right sides and that the signal intensity is linearly proportional to the sound pressure, as indicated by Equation (1). Those characteristics are experimentally verified.

Figure 6 shows the cross-section of light beam measured at the observing plane. The x-coordinate is the distance from the origin of the x-z scanning stage. The radius of light beam is estimated to be about 0.5 mm by taking the photodetector diameter of 0.4 mm into consideration.

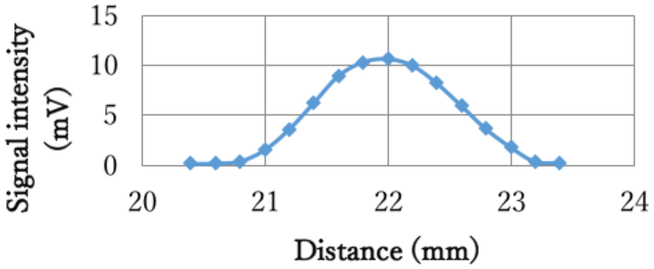


Figure 6. Cross-section of light beam at observing plane

When a sound crosses the light beam between lens 2 and lens 3, Doppler-shifted diffraction light occurs. The spatial pattern of it is measured and Figure 7 shows the result. Though weak asymmetry between the left and right sides in Figure 7 appears, it has two peaks as indicated in Figure 2(a) calculated by the fundamental theory. As the cause of the asymmetry, the spatial spread and the indefiniteness of incidence angle of sound are predicted. Because the degree of asymmetry is considered as a tolerance level, the photodetector is set at the left peak position in Figure 7 in the next experiment measuring sound pressure property.

Furthermore, the sound pressure property of this system was measured. Figure 8 shows the experimental result for relation between sound pressure and signal intensity. It is found that the signal intensity is proportional to sound pressure under the present experimental condition from 0.6 Pa to 20 Pa. It is consistent with the theoretical prediction.

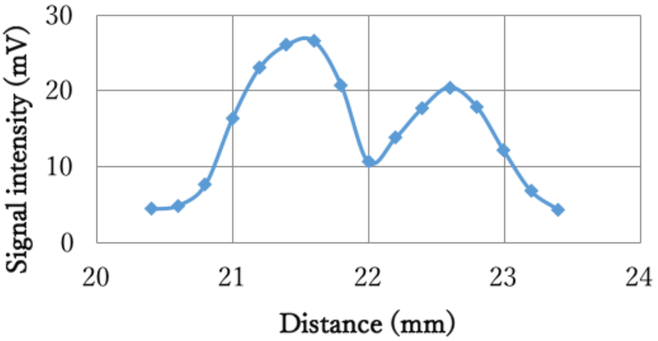


Figure 7. Spatial intensity pattern of diffraction light

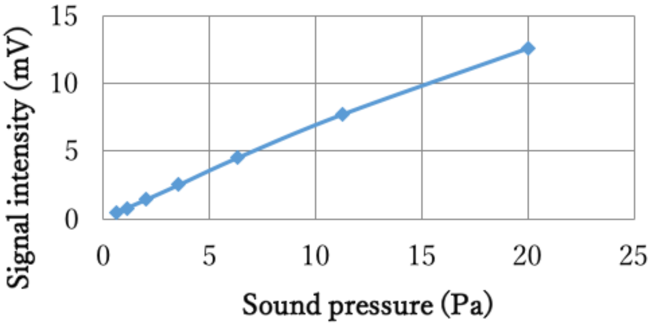


Figure 8. Sound pressure property

5. Conclusions.

The feasibility study to verify the possibility of the optical wave microphone using an LED light source was carried out. It was shown that LED is useful as a light source of the optical wave microphone. Furthermore, some sound receiving properties were experimentally examined and it was found that the signal intensity was proportional to sound pressure.

As the preliminary study has just started, the systematic and quantitative estimations are more required for exact understanding of the LED optical wave microphone, which are now in progress.

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