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SOUND DETECTION LIMIT IN OPTICAL WAVE MICROPHONE SYSTEM WITH LONG LASER BEAM TRANSMISSION AND IMPROVEMENT OF SIGNAL TO NOISE RATIO

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Abstract. *Application of the optical wave microphone, which directly detects audible sounds by a laser beam without any diaphragm, to a long laser beam sound antenna is discussed. In order to clarify the sound detection limit of the optical wave microphone system using a long complexed laser beam transmission, the minimum return laser power needed to detect audible sounds is experimentally examined. The relationship between the laser power returned to the receiving optics and the signal intensity is measured and it is found that the minimum return laser power to detect the sound pressure level of 90 dB is about 0.03 mW. Based on the obtained value, the signal to noise ratio of the present system for each sound frequency and sound pressure level is estimated. Subsequently, in order to improve the weak signal intensity, the external local oscillating power is applied to the optical heterodyne detection in this method, showing that the output signal is amplified by it and the intensity is proportional to the square root of local power.*
Keywords: Optical wave microphone, Retroreflector, Laser beam, Laser-aided sound antenna, Remote sensing, Sound security system

1. **Introduction.** As a representative method to measure sounds, various kinds of microphones have been developed and used over a hundred years. Since all of these use a diaphragm and they must be set at the measurement point, many restrictions come out in practical applications, for example, in the case of sound monitoring or watching of a wide security area. On the other hand, a novel sound measurement method based on wave-optics or the optical wave microphone (OWM), which directly detects audible sounds by a laser beam without any diaphragm, was proposed [1,2] and the fundamental technique has been developed [3-6]. Furthermore, in order to improve the signal to noise ratio, some soft computing methods have been studied [7,8]. The OWM is expected to be extremely useful for a sound security system or sound monitoring of a wide security area, because a very long sound sensing antenna can be easily constructed by using a laser beam. In the previous report, we proposed the improved OWM using a retroreflector for this purpose and the validity of it was experimentally verified [9]. However, in the case of the complicated beam transmission covering a long distance, optical signal detection limit appears because the laser power is attenuated through the long-distance propagation and the output signal intensity becomes lower than noise level.

In the present study, first, sound detection limit or minimum return laser power in our present measurement system is experimentally examined. Based on the result, the

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signal to noise ratio of present system for each sound frequency and sound pressure level is estimated. Furthermore, in order to improve the performance, heterodyne detection using the external local oscillating power is proposed and experimentally examined.

In Section 2, the theory of the optical wave microphone and the construction of the improved retroreflector are shortly introduced. The experimental apparatus and method for this research are shown in Section 3, and the experimental result and consideration are described in Section 4. The last chapter is the conclusion of this study.

2. Principle.

2.1. Abstract of measurement theory. The theoretical model for the OWM is shown in Figure 1, in which the lens on the left-hand side is for adjustment of the incident laser beam size, and one on the right-hand side is for the main optical signal processing or the optical Fourier transforming. When a sound wave crosses the laser beam, ultra-small Doppler-shifted diffraction light is generated. It passes through a receiving lens (focal length; f_1 [m]) with the penetrating laser beam and is detected by a photodetector at the back focal plane, finally giving an electrical output signal.

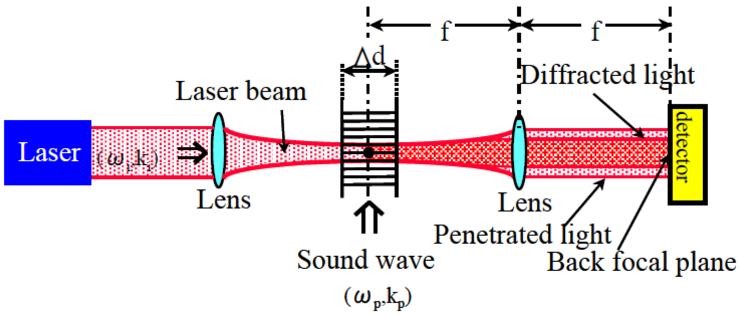


FIGURE 1. Theoretical model

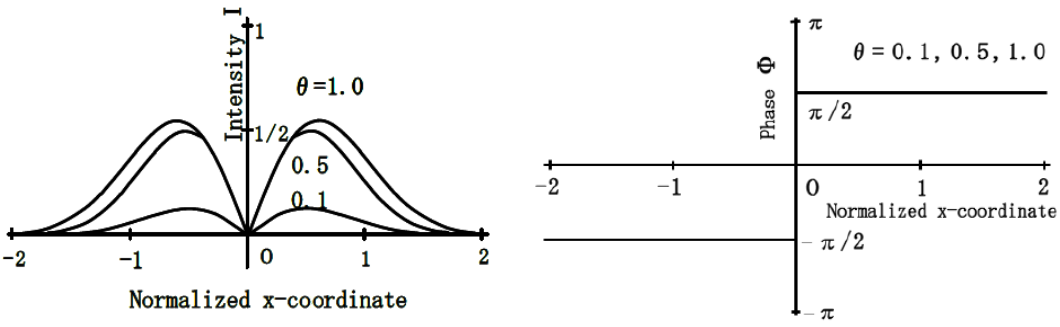
The signal intensity I_{ac} [W/m^2] obtained at the observing plane is given by the following equation [10,11].

$$I_{ac} = I_0 \Delta\phi_0 \left[\exp\left\{-\left(u^2 + (u-\theta)^2\right)\right\} + \exp\left\{-\left(u^2 + (u+\theta)^2\right)\right\}\right] \sin \omega_a t \qquad (1)$$

where $I_0 = (2P_0/\pi {w_f}^2) \exp\left[-2\left(y_f/w_f\right)^2\right]$ [W/m^2], $\Delta\phi = k_i(\mu_0 - 1)\Delta z \Delta p/\gamma p$, μ_0: refractive index of air, γ: specific heat ratio, Δz: 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, $u = x_f/y_f$: 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 incident region, w_f, x_f, y_f: radius of beam cross section, x-coordinate and y-coordinate in the observing plane, respectively.

Based on the above Equation (1), the theoretical diffraction pattern can be calculated. Examples of spatial distributions of the intensity and the phase of the diffraction pattern are shown in Figures 2(a) and 2(b), respectively. In Figure 2(a), the spatial intensity profile of diffraction light pattern generated by a sound wave has two peaks. However, the temporal phase difference between the right and left diffraction patterns is π, as shown in Figure 2(b). The output sound signal is obtained by setting a photodetector at one of two peaks. Inversely, if setting a photodetector over two peaks, no signal is gained because of cancellation between two peak signals.

2.2. Abstract of improved retroreflector with a supplemental plate mirror. As well known, a retroreflector gives a reflected beam that is precisely parallel to the incident beam, independent of the angle of incidence. However, in the case of standard

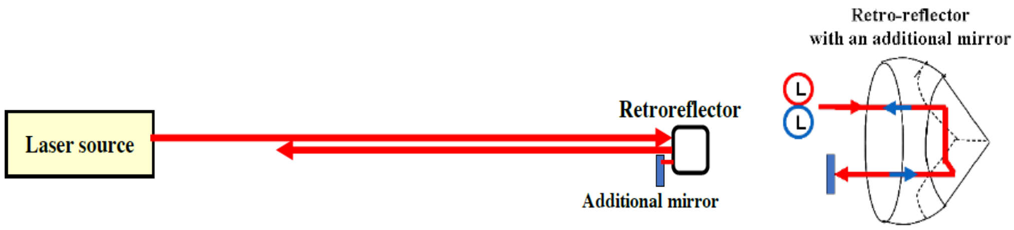


(a) Intensity distribution (b) Phase distribution

Figure 2. Theoretical calculation of diffraction spatial distribution

retroreflector, the reflected beam propagates with horizontal and vertical reverse state compared with the incident beam and it cannot be used for the OWM.

The improved retroreflector with a supplemental plane mirror was proposed in the previous study [9], as shown in Figures 3(a) and 3(b). In this construction, the first reflected beam is again reflected by a plane mirror and is returned to the retroreflector again. In this case, the final reflected beam from the improved retroreflector is without being inverted horizontally and vertically. That is, the final signal intensity is theoretically expected to be twice the signal intensity in single beam measurement.



(a) Beam transmission by improved retroreflector (b) Improved retroreflector with a supplement mirror

Figure 3. Construction of improved retroreflector and beam transmission

3. **Experimental Apparatus and Method.** The arrangement of experimental device is shown in Figure 4. The visible diode laser (wavelength 635 nm, output power 25 mW) is used. The radius of laser beam is 1.5 mm. To avoid the reflection light returning to the laser source, an optical isolator is set between the laser source and a beam splitter. The laser beam output from the laser source is split into two beams by the beam splitter (split ratio: 1 : 1). One of these propagates straightly to the retroreflector and the other is perpendicularly bent and absorbed by an optical absorber. The insertion loss of the improved retroreflector is about 35%. When the external oscillating power is used in heterodyne detection experiment, it is replaced by a mirror with an attenuator (B). The laser beam reflected by the retroreflector is again split into two beams, that is, the optical signal processing side and the laser source side. The beam transmitted to laser source side is stopped by the isolator. When the input power to sound measurement region and the returned power are controlled, another attenuator (A) is used. On the other hand, the signal beam propagating to optical processing side passes through three lenses (from No.1 to No.3) and is detected by a photodetector. By these three lenses, optical Fourier transforming and arranging the beam size are performed. The first lens No.1 (f_1 = 200 mm) is the main lens to do optical Fourier transform. By the lens No.2 (f_2 = 6 mm) and lens No.3 (f_3 = 200 mm), the laser beam diameter and the diffraction pattern size

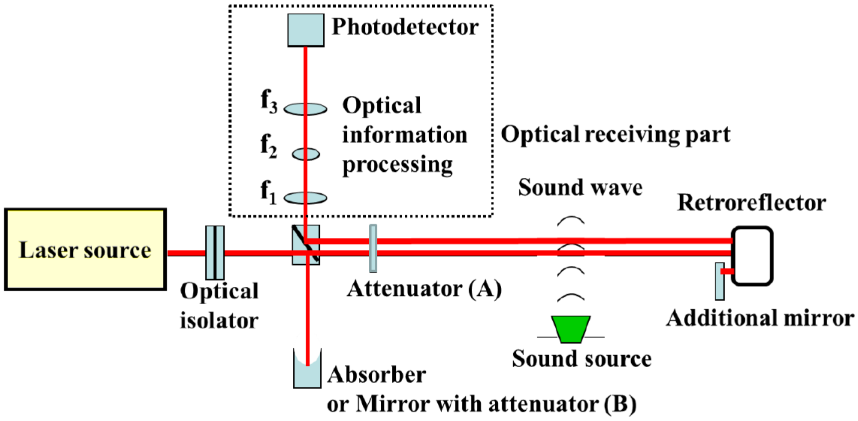


FIGURE 4. Experimental apparatus

are enlarged. The beam radius at the observing plane is about 1 mm. Since the incident and reflected laser beams in sound measurement region are parallel each other and have the same diameter at any point in the sound measurement region, the sound detection sensitivity is same at both the incident beam and the reflected beam.

As an oscillating source of a test sound wave, a small ultrasonic oscillator (frequency 25 kHz, outer diameter 16 mm) is used. It is set at position of 150 mm from the beam splitter. The transmitted sound is perpendicularly injected into the laser beam from horizontal direction. The sound pressure level is monitored by a 1/4 inch electrostatic microphone (20 Hz – 200 kHz; Flat property). The distance between the laser beam axis and the surface of the sound transmitter is 90 mm, and the sound pressure level at the laser beam axis is set to 90 dB. The sound pressure level of the background noise is under about 50 to 60 dB. The width of the sound wave at the laser beam axis is about 90 mm.

In the optical receiving part which is constructed by three lenses and a photodetector as shown in Figure 4, a small photodiode (diameter: 0.2 mm, sensitivity: 0.4 A/W) is used as a photo-sensor. The sound signal or the alternating component is picked out to a preamplifier through a coupling capacitor. The electrical signal is amplified 10 times by a preamplifier. The output signal from it is input into a band-pass filter with amplifier (15 kHz – 35 kHz; amplification factor 25) and finally into a frequency analyzer or a digital oscilloscope and is saved by a personal computer.

4. Experimental Results and Discussion.

4.1. Measurement of spatial diffraction light profile. As the present experimental room is too narrow to set up a few 10 m laser beams, the distance between the beam splitter and the retroreflector is set about 600 mm. First of all, we measured the spatial profile of diffraction light pattern at the observing plane. An example of frequency spectrum of signal is shown in Figure 5, in which the photodetector is set near the peak position of diffraction pattern. The signal is observed at frequency of 25 kHz, which is the same with the sound frequency. The waves observed below about 2 kHz are electrical and background noises. By horizontally scanning the detector, we measured the spatial profile of the diffraction light intensity. The experimental result is shown in Figure 6. In this figure, the spatial profile with two peaks is obtained, which is consistent with the theoretical prediction indicated in Section 2.1. From the results, it is experimentally confirmed that the measurement system constructed here is certainly operating to detect sounds.

4.2. Relation between return laser power and signal intensity. In this section, the laser power returned to the optical receiving part shown in Figure 4, is discussed. In the complexed laser beam transmission covering a long distance, the return laser power

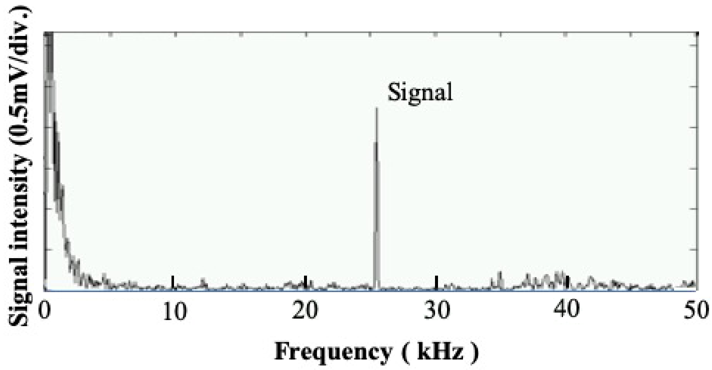


FIGURE 5. An example of frequency spectrum signal

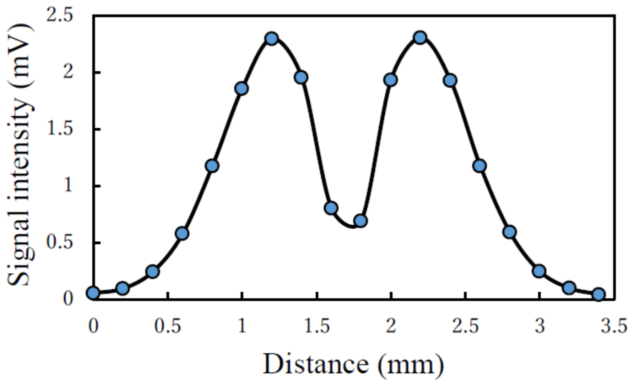


FIGURE 6. An example of measured diffraction profile

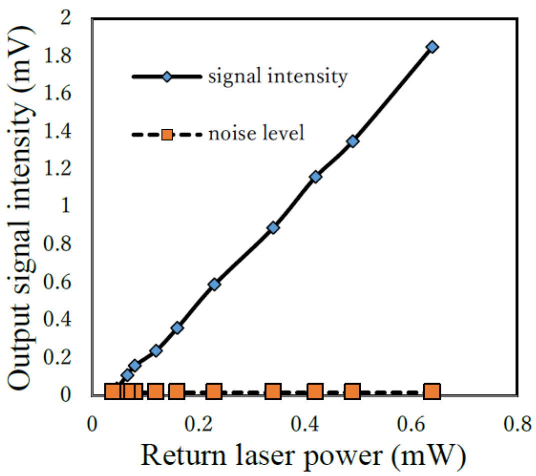


FIGURE 7. Relationship between return laser power and signal intensity

P_{re} often becomes very small. The experiment to find the minimum return laser power needed to detect sound was carried out. The sound pressure level was set 90 dB at the laser beam axis. Figure 7 shows the obtained relationship between the return laser power and the signal intensity. It is found that the signal intensity is nearly proportional to P_{re} and the minimum return laser power is about 0.03 mW.

4.3. **Estimation of SNR for any frequency and sound pressure level.** When P_{re} is 0.2 mW in Figure 7, SNR is estimated to be about 19.2 for the input sound of 25 kHz, 90 dB. Based on the obtained value, signal to noise ratio (SNR) for P_{re} = 0.2 mW is

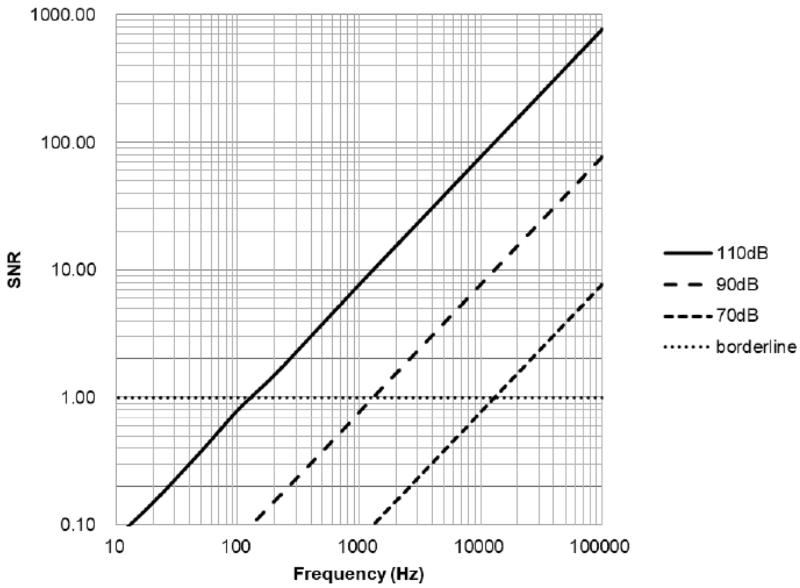


Figure 8. SNR for return laser power of 0.2 mW (Sound pressure level: 110 dB, 90 dB, 70 dB)

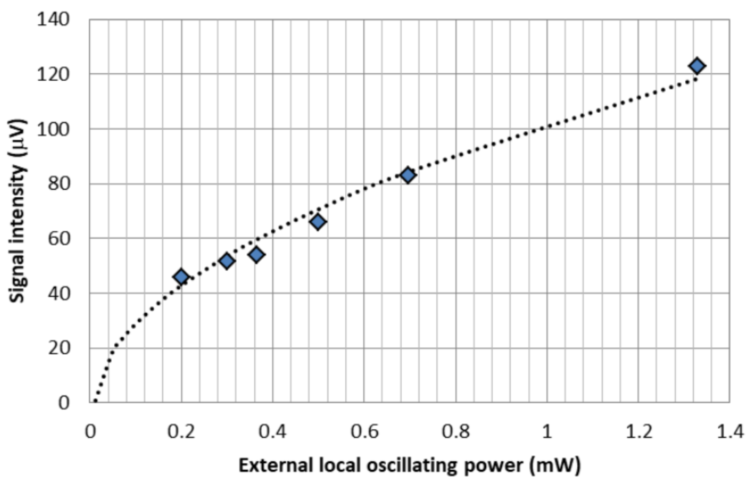


Figure 9. Relation between signal intensity and external local oscillating power

calculated. The result is shown in Figure 8, in which the borderline (SNR = 1) indicates detection limit.

4.4. **Signal amplification by superimposing of external local oscillating power.** In order to improve the sound detection performance, we tried to superimpose the external local oscillating power P_l for heterodyne detection in OWM. It is theoretically predicted that the signal intensity is proportional to $((P_l + P_{re})/P_{re})^{1/2}$, if the wave-front and phase of local oscillating light are coincided with those of penetrating light, respectively. If $P_l >> P_{re}$ is satisfied, the output signal is proportional to $(P_l/P_{re})^{1/2}$. As P_{re} is constant, the signal is proportional to $(P_l)^{1/2}$. In the present experiment, P_l is changed from 0.2 mW to 1.3 mW by the attenuator (B) in Figure 4. The return laser power is set about 0.15 mW. The obtained relation between P_l and signal intensity is shown in Figure 9. It is found that the output signal intensity is amplified and nearly proportional to $(P_l)^{1/2}$ except the special condition in which P_l is not so larger than P_{re}. In the present system, this method is expected to be very useful, when P_{re} is extremely smaller than 1 mW.

5. **Conclusion.** Application of OWM to a long laser beam sound antenna or a sound security system is discussed. In order to clarify the sound detection limit of OWM system using a long complexed laser beam transmission, the minimum return laser power needed to detect audible sounds is experimentally obtained. The relationship between the laser power returned to the receiving optics and the signal intensity is measured and the minimum return laser power to detect sound is obtained. Based on the measured value, the signal to noise ratio for each sound frequency and sound pressure level is estimated. Subsequently, in order to improve the weak signal intensity, the external local oscillating power is applied to the optical heterodyne detection in this method, showing that the output signal is amplified by it and the intensity is proportional to the square root of local power. Furthermore, some soft computing methods such as a deep neural network are to be developed to achieve better performance.

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