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DEVELOPMENT OF OPTICAL WAVE MICROPHONE WITH RETROREFLECTOR FOR REMOTE SENSING AND SOUND SECURITY SYSTEM

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Abstract. *The optical wave microphone method with no diaphragm is based on waveoptics and can detect sounds by a laser beam without disturbing sound field. In order to apply it to remote sensing or sound security system, the retroreflection in a long laser beam system is experimentally discussed. Especially, the improved retroreflector, which reflects the laser beam without being inverted horizontally and vertically, is presented. The possibility of the optical wave microphone using it is examined by experiments, demonstrating that it is very effective to detect sounds and can be applied in the field of remote sensing or sound security system.*

Keywords: Optical wave microphone, Retroreflector, Laser beam, Beam antenna, Remote sensing, Sound security system

1. **Introduction.** As a powerful method to measure sounds, various microphones have been developed. These usually use any diaphragm to detect sound and change it into an electric signal. In this method, as an electrical sensor has to be set at the measurement point, various restrictions come out in practical applications. For example, in case of sound monitoring or watching of a wide security area, many sensors must be set at different spatial positions and the connecting electric wirings for these also become complicated.

On the other hand, as a novel optical sound detection method with no diaphragm, the optical wave microphone, which is based on the wave-optics and directly detects audio waves by a laser beam, was proposed by us [1,2]. And the fundamental techniques have been developed [3-6]. Furthermore, some researches about the soft computing to improve the signal-to-noise ratio (SN-ratio) have been carried out, showing that it was improved by 10 to 23 dB and sounds higher than about 50 dB could be detected [7,8].

In this method, if a sound wave crosses a laser beam propagating in air, the laser light receives weak phase modulation by the refractive-index fluctuation of the sound wave and the extremely weak diffraction light is generated. It passes through an optical information-processing optics with the penetrating laser light and finally these are detected by a photodetector and the electrical output signal is obtained. It has many advantages over the conventional solid microphone. One of these is that a very long sound sensor or sound

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sensing beam antenna can be constructed by using a long laser beam, which is expected to be very useful for a sound security system. For example, it can measure sounds around a large important secrecy building or factories; furthermore, it can monitor suspicious sounds along the beach of Sea of Japan for border security.

When using a long-distance laser beam, a mirror is usually set at a remote position or a target point and the reflected laser beam is detected at the original laser-source place, which is more effective than setting a receiving device in the remote place. However, if a simple flat mirror is used to construct a long-distance laser beam system, it has to be set precisely perpendicular to the incident laser beam. And the system is often strongly disturbed by a small angle variation or vibration. For such practical cases, a retroreflector is very useful and often used in the practical measurements. It gives the reflected laser beam that is precisely parallel to the incident beam, independent of the angle of incidence. For the present remote sound detection system, it is expected to be extremely effective. However, as the laser beam reflected by the usual retroreflector is in a horizontal and vertical inversion state compared with the incident laser beam, the two diffraction light patterns, which are originally generated at both of the incident and reflected beams crossing a sound wave respectively, will cancel out each other and the total output electrical signal cannot be obtained.

In this research, the improved retroreflector with an auxiliary plate mirror, which reflects the laser beam without being inverted horizontally nor vertically, is proposed. Furthermore, the feasibility and the receiving property of the modified optical wave microphone using it, are experimentally verified.

The theory of the optical wave microphone and the construction of the improved retroreflector are introduced in Section 2, the total 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 a conclusion of this study.

2. Principle.

2.1. Abstract of measurement theory. The theoretical model for the optical wave microphone is shown in Figure 1. In this figure, the lens on the left-hand side is for adjustment of the incident laser beam size, and one on right-hand side is for optical signal processing or the optical Fourier transforming. When a sound wave crosses the laser beam, ultra-small diffraction light, which is Doppler-shifted with the sound frequency, 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 observing plane, finally giving an electrical output signal.

When a sound wave crosses the beam waist of probing laser beam as shown in Figure 1, the signal intensity I_{ac} [W/m^2] obtained at the observing plane is given by the following

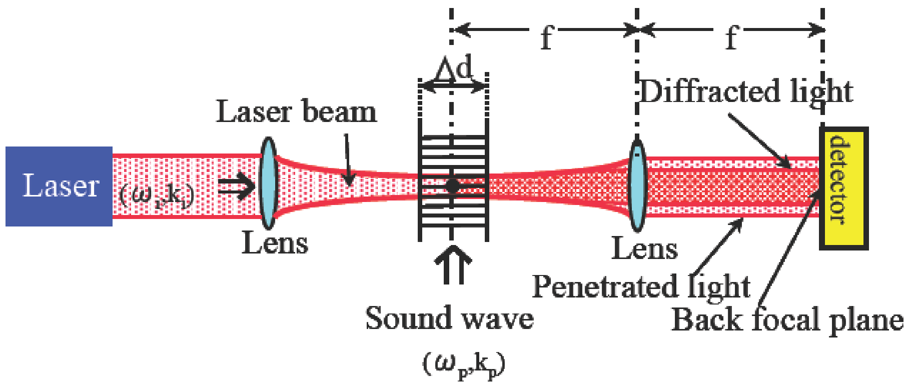


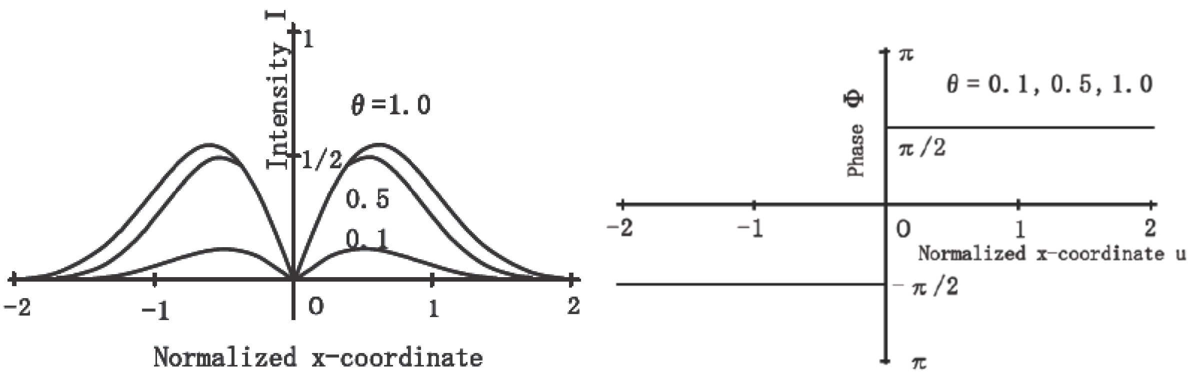
FIGURE 1. Theoretical model

equation [9,10].

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

where $I_0 = \left(2P_0/\pi w_f^2\right)\exp\left[-2(y_f/w_f)^2\right]$ [W/m^2], $\Delta\phi = k_i(\mu_0 - 1)\Delta d\Delta p/\gamma p$, 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_p: angular frequency of sound wave, P_0: laser power, $u = x_f/y_f$: the normalized x-coordinate in the back focal plane, $\theta = k_p w_0/2$: the normalized wave number, k_p: 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), numerical calculations of the diffraction pattern are carried out. 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 gained by setting a photodetector at one of two peaks. Inversely, if setting a detector over two peaks, no signal is obtained because of cancellation between two peak signals.



(a) Intensity distribution (b) Phase distribution

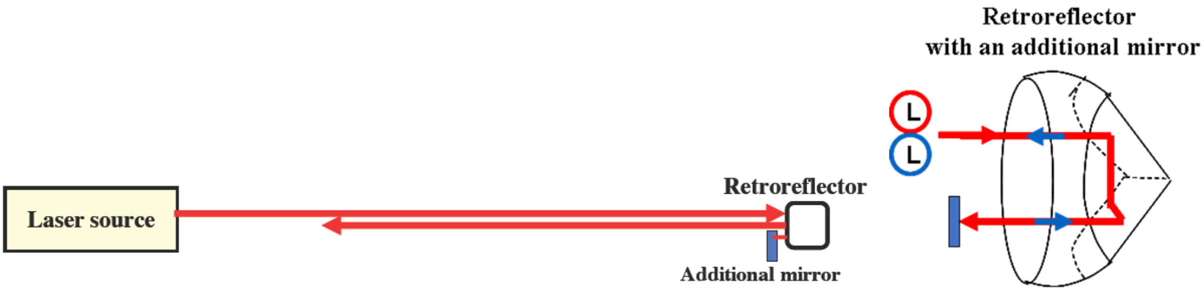
Figure 2. Theoretical calculation of diffraction spatial distribution

2.2. **Construction 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. Then, if we can utilize it for sound detection by the optical wave microphone with a long distance laser beam, it becomes greatly effective to construct the optical measurement system. However, in case of the standard retroreflector, the reflected beam propagates with horizontal and vertical reverse state compared with the incident beam as shown in Figures 3(a) and 3(b). When a sound wave crosses the both-way beam, the two diffraction light patterns with two peaks, which are generated in the incident beam and the reflected beam respectively, are superimposed in the observing plane. That is, if we try to perform sound detection by using the standard retroreflector, the output signal will no longer be acquired because of cancelation between two diffraction light patterns generated at both incident and reflection laser beams, respectively.

On the other hand, the improved retroreflector with a supplemental plane mirror proposed in the present study is shown in Figures 4(a) and 4(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 sound signal can be obtained and

(a) Beam transmission by retroreflector (b) Standard retroreflector

Figure 3. Construction of retroreflector and beam transmission



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

Figure 4. Construction of improved retroreflector and beam transmission

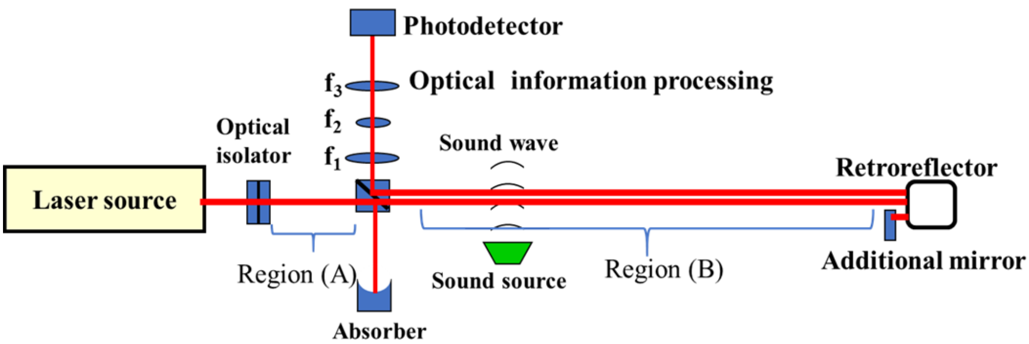


Figure 5. Experimental apparatus

the final intensity is theoretically expected to be twice the signal intensity of single beam measurement.

In this research, first of all, the characteristic of sound detection using a standard retroreflector is experimentally checked and discussed. Next, the possibility and the receiving property of the optical wave microphone using the improved retroreflector which reflects laser beam without horizontal and vertical inversions, are experimentally verified.

3. **Experimental Apparatus and Method.** The arrangement of experimental device is shown in Figure 5, in which the improved retroreflector is written for the time being. 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: 2:1). One of these propagates straightly to the retroreflector and the other is perpendicularly bent and absorbed by an optical absorber. 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. 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 adjusting the beam size are performed. The first lens No.1 (f_1 = 200 mm) is 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 or the diffraction pattern size is 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 to each other and have the same diameter at any point in the sound measurement region, the sound detection sensitivity is the same at both the incident beam and the reflected beam. In Figure 5, the region (A) means the space between the isolator and the beam splitter where a single beam is propagating and the region (B) means the space between the beam splitter and the retroreflector where the incident and reflected beams are propagating.

As an oscillating source of a test sound wave, a small ultrasonic oscillator (frequency 25 kHz, outer diameter 16 mm) is used. 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 95 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.

As a photosensor, a small photodiode (diameter: 0.2 mm, sensitivity: 0.4 A/W) is used. 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 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.** Before doing the main experiment using the improved retroreflector, we set up a standard retroreflector and carried out the pre-experiment. As the present experimental room is too narrow to set up a few 10 m laser beam, 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 at the observing plane when a test sound wave was injected to the region (A), where a single laser beam was propagating. An example of frequency spectrum of signal is shown in Figure 6, 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 as the sound frequency. By horizontally scanning the detector, we measured the spatial profile of the diffraction

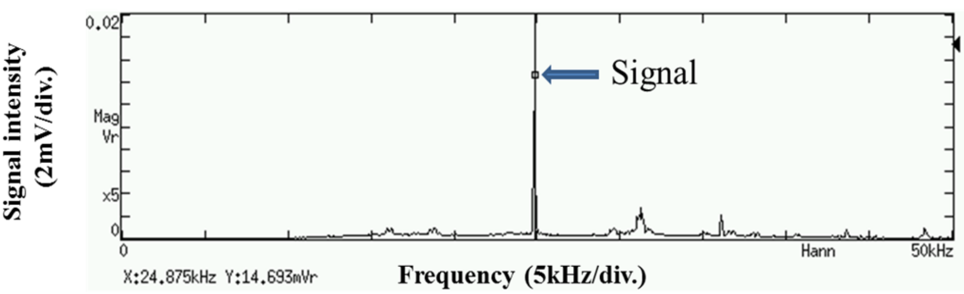


Figure 6. An example of frequency spectrum signal for single beam measurement

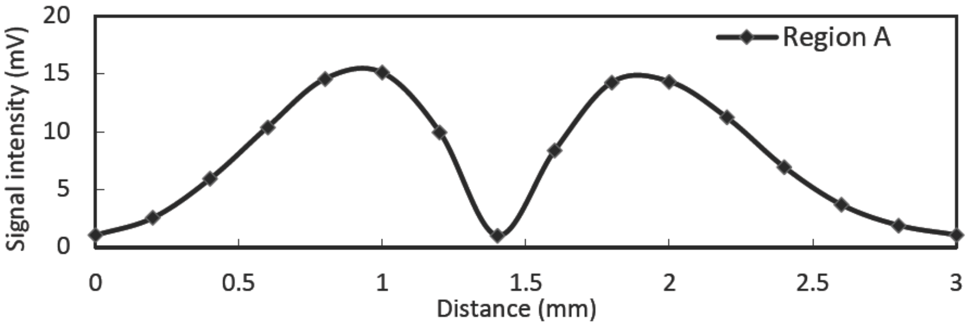


Figure 7. An example of measured diffraction profile

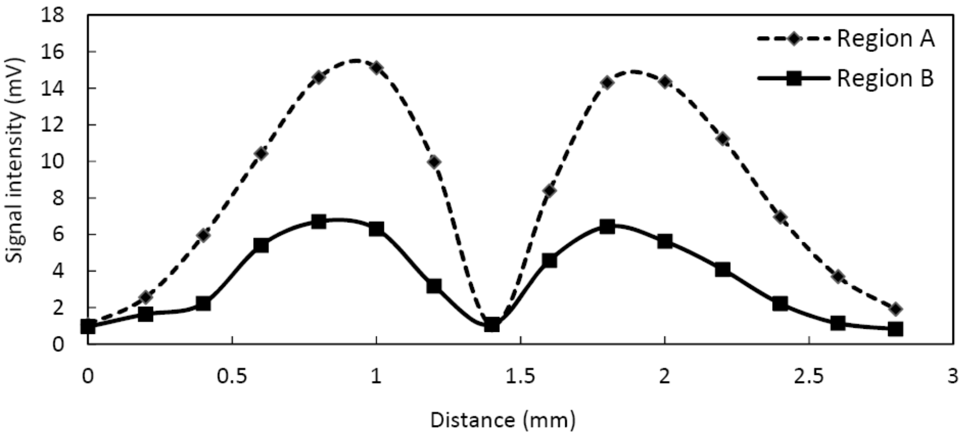


Figure 8. Signals for both-way beam measurement using a standard retroreflector

light. The experimental result is shown in Figure 7. In this figure, the spatial profile with two peaks is obtained, which is consistent with the theoretical prediction indicated in Section 2.1. From these results, it is experimentally confirmed that the measurement system constructed here is certainly operating to detect sounds.

4.2. **Relation between signal intensity and sound incident region for laser measurement system with standard retroreflector.** For the optical system with a usual retroreflector, the test sound was injected to the region (A) and next the region (B) and the signal intensities for both cases were compared with each other. The incident and reflected laser beams were collimated and parallel to each other in the region (B). The obtained spatial profiles of diffraction light pattern are shown in Figure 8, in which the dotted line is for the region (A) and the solid line is for the region (B). In the region (B), the sound injection position was separated about 150 mm from the beam splitter. Though it is theoretically expected that no signal is gained for the incidence to the region (B) because of the reciprocal reflection by the usual retroreflector, the small signal is observed in Figure 8. It is presumed that as the laser power of reflected beam is decreased about 35% by insertion loss of the present retroreflector with low performance and a small twisting of the reflected beam exists, the cancellation between two diffraction light signals generated in the incident and reflected beams is not perfect. If the retroreflector with high performance or low insertion loss is used, the signal for the region (B) approaches to zero, as theoretically surmised. However, from these results, it is concluded that if the standard retroreflector is used for beam transmission of the optical wave microphone, the sound detection becomes difficult or the detection sensitivity becomes very low.

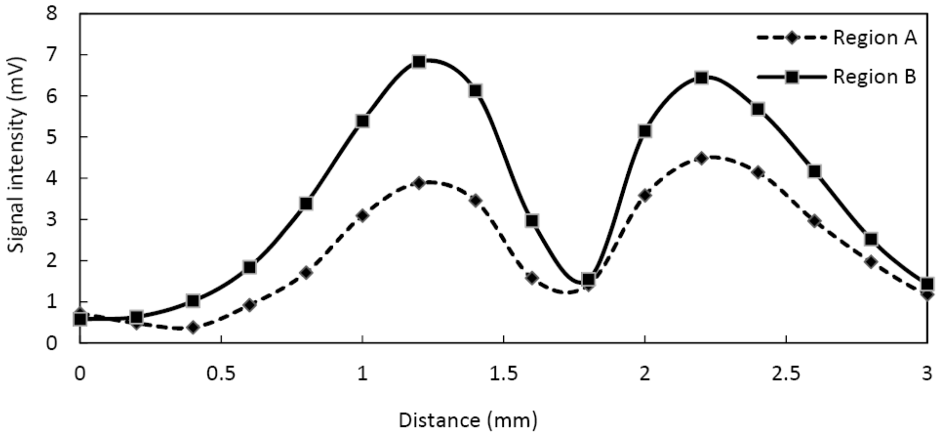


Figure 9. Signals for both-way beam measurement using improved retroreflector

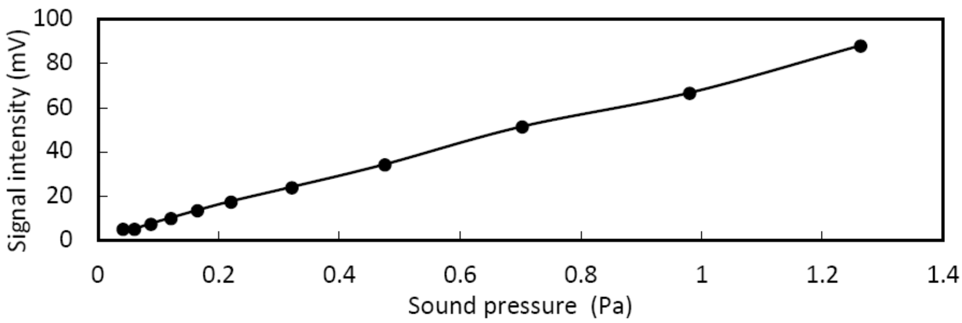


Figure 10. Sound pressure property of optical wave microphone system with improved retroreflector

4.3. **Relation between signal intensity and sound incident region for laser measurement system with improved retroreflector.** After setting the improved retroreflector with an additional mirror as shown in Figure 4 and Figure 5 instead of the standard retroreflector, the next main experiment was carried out. The experimental condition was the same as the preceding experiment described in Section 4.2. The obtained spatial profiles of diffraction light pattern are shown in Figure 9, in which the dotted line is for the region (A) and the solid line is for the region (B). It is expected that if the ideal or perfect retro-reflection is achieved, the signal intensity for the region (B) becomes twice for the region (A) or single beam measurement. In the experimental result shown in Figure 9, it is found that the signal intensity for the region (B) is about 1.6 times the intensity for the region (A), which is smaller than 2 or the ideal value. However, if the insertion loss (59%) of the improved retroreflector and a small twisting of the reflected beam are taken into consideration, the obtained value is thought to be reasonable. From results shown above, it is concluded that if the improved retroreflector with a supplemental flat mirror presented in this study is used for long laser beam transmission of the optical wave microphone, the sound detection becomes possible, and then the sound detection sensitivity becomes two times for the single beam measurement.

4.4. **Sound pressure property.** In addition to the verification of ability of the optical wave microphone system with the improved retroreflector, the sound receiving property or the sound pressure property of the present system was experimentally examined. In this experiment, the photodetector was set at the left peak position of the spatial diffraction profile. The experimental result is shown in Figure 10. It is found that the signal intensity is linearly proportional to the sound-pressure from 0.04 to 1.26 Pa, which property is thought to be very useful for various applications.

5. **Conclusion.** When using the optical wave microphone with a long laser beam for remote sound sensing or sound monitoring in wide security region or space, the retro-reflection system is very convenient and useful. However, the standard retroreflector with all three components of reflected beam direction exactly reversed cannot be used for the sound detection by the optical wave microphone. In the present study, the long laser beam system using retroreflection is experimentally discussed. In order to realize a retro reflection measurement, the improved retroreflector with an additional flat mirror is proposed and the validity of it is experimentally verified. The optical wave microphone with the improved retroreflector is expected to be very useful for remote sensing and sound security system.

In the present machine, the total performance, especially the SN-ratio is not enough to detect sound pressure level under about 50 dB. In order to improve it, instead of the previous methods [7,8], other superior soft computing methods such as a deep neural network are to be developed in the next study.

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