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*Review Article*

# Development of Optophone with No Diaphragm and Application to Sound Measurement in Jet Flow

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The optophone with no diaphragm, which can detect sound waves without disturbing flow of air and sound field, is presented as a novel sound measurement technique and the present status of development is reviewed in this paper. The method is principally based on the Fourier optics and the sound signal is obtained by detecting ultrasmall diffraction light generated from phase modulation by sounds. The principle and theory, which have been originally developed as a plasma diagnostic technique to measure electron density fluctuations in the nuclear fusion research, are briefly introduced. Based on the theoretical analysis, property and merits as a wave-optical sound detection are presented, and the fundamental experiments and results obtained so far are reviewed. It is shown that sounds from about 100 Hz to 100 kHz can be simultaneously detected by a visible laser beam, and the method is very useful to sound measurement in aeroacoustics. Finally, present main problems of the optophone for practical uses in sound and/or noise measurements and the image of technology expected in the future are shortly shown.

## 1. Introduction

As a standard technique to measure sound waves, various types of microphone have been developed and used over one hundred years. However, they have many restrictions on practical applications, especially for sound measurement in flow of air or aeroacoustic phenomena, because they use a solid diaphragm or any vibrating object to detect sound waves. On the other hand, the light diffraction method is very effective to measure any refraction-index waves, such as high-frequency ultrasonic waves in solid or liquid, with no disturbance and has been established in the field of acoustooptics and used in many applications [1]. But the conventional light diffraction method cannot be applied to the measurement of sound waves in air with long wavelength, in which the diffracted signal light is extremely weak and also propagates in the penetrating optical beam and cannot be detected by the disturbance of the latter.

The optical wave microphone (or the optophone) based on the wave optics is excellent and valuable in measuring sounds of very long wavelengths, which have not ever been treated in the conventional acoustooptics. The method is based on the theory of the Fraunhofer diffraction method, which was developed as a new means to detect the electromagnetic radiation scattered by long-wavelength plasma waves within the penetrating laser beam in the plasma nuclear fusion research [2, 3]. After that, the method has been applied to sound measurement from audio to ultrasonic waves and developed by authors in Japan [4, 5]. By such special history of development, the optophone is not well known to sound researchers in the world. In this paper, the present status of the optophone, including the theory, hardware, property and expected future technology, is briefly reviewed and widely introduced to sound researchers.

## 2. Principle and Theory

The original theory was developed as a plasma wave diagnostic technique in the plasma nuclear fusion research field [2, 3]. By using the theory, the fundamental measurement theory of the optophone has been already established. The image of the optophone of one-dimensional straight laser beam type is shown in Figure 1. The fundamental optical setup of the method for theoretical analysis is shown in Figure 2.

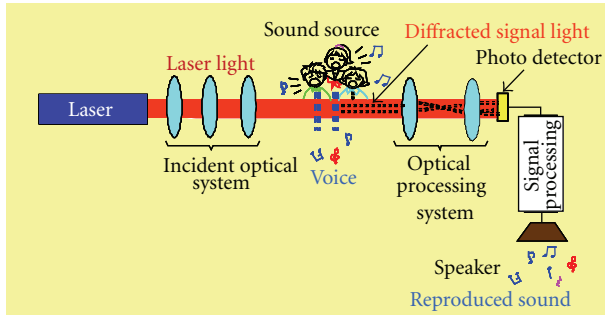



Figure 1: Image of the optical wave microphone.

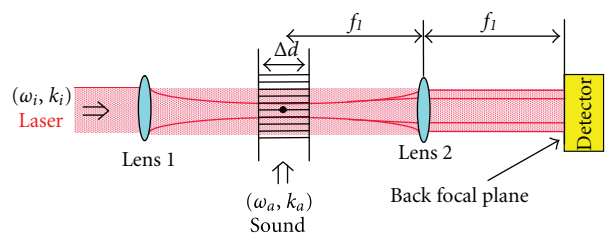



Figure 2: Optical setup for theoretical analysis.

When an incident probing laser beam crosses an acoustic wave, diffracted light waves are generated and propagate with and in the penetrating beam through the Fourier optical system and reach the observing plane, which is set in the back focal plane of a receiving lens.

The distribution of light in the observing plane $u(x_f, y_f)$ is calculated by using the Fresnel-Kirchhoff's equation as follows:

$$u(x_f, y_f) = \left\{\frac{i\exp(-2k_i f_1)}{\lambda_i f_1}\right\} \iint_{-\infty}^{+\infty} u(x_0, y_0)\, T(x_0, y_0) \times \exp\left\{\frac{ik_i(x_0 x_f + y_0 y_f)}{f_1}\right\} dx_0\, dy_0, \quad (1)$$

where $u(x_0, y_0)$ is complex amplitude of incident laser beam, $T(x_0, y_0)$ is phase modulation by sound, $(x_0, y_0)$ is coordinate of sound incident plane, $(x_f, y_f)$ is coordinate of observing plane, $f_1$ is focal length of lens, and $(k_i, \lambda_i)$ is wave number and wavelength of laser light, respectively.

In this condition, the intensity of diffracted light of higher orders or multiple diffraction is much smaller than that of the first order light and can be neglected. In the practical machine, the electrical output from a photo detector includes both the DC component and the AC component relating to Doppler-shifted diffraction light. The DC component is removed in the electric circuit, and only the 1st AC component is used. The spatial intensity of diffraction light signal for the theoretical model shown in Figure 2 is given by the following equation [2, 3]:

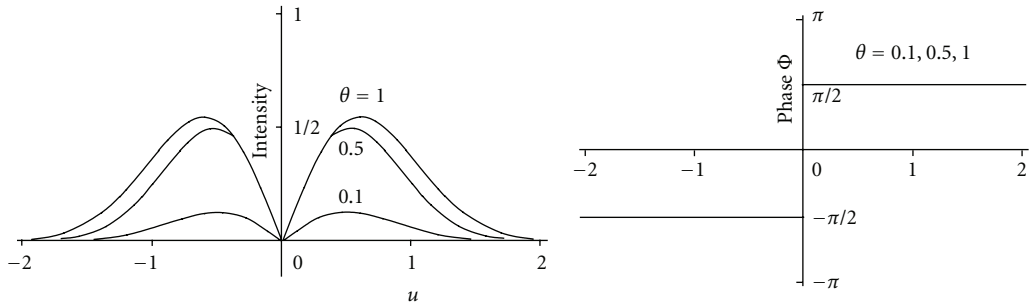
$$I_{\mathrm{ac}}^{(1)} = I_0 \Delta\phi \exp(-u^2) \times \left[\exp\left\{-(u-\theta)^2\right\} - \exp\left\{-(u+\theta)^2\right\}\right] \cos\omega_a t, \quad (2)$$

where $I_0 = (2P_0/\pi w_f{}^2)\exp\{-2(y_f/w_f)^2\}$, $\Delta\phi = k_i(\mu_0 - 1)\Delta d \Delta p/\gamma p$, $\mu_0$: refractive index of air, $\gamma$: specific heat ratio, $\Delta d$: width of sound, $p$: atmospheric pressure, $\Delta p$: sound pressure, $\omega_a$: 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 incident region, and $w_f$: radius of laser beam in the observing plane, respectively.

Based on the above equations, numerical calculations of the diffraction pattern were carried out, in which a visible laser was assumed as a probing laser beam. Examples of spatial distributions of the intensity and the phase of the diffraction pattern are shown in Figures 3(a) and 3(b), respectively. The spatial profile of diffracted light pattern ($I$) oscillating at the sound frequency has two peaks, which spatial positions do not change with frequency in the audiowave or the low-frequency ultrasonic band. On the other hand, the temporal phase difference ($\Phi$) between the right and left diffraction patterns oscillating at $\omega_a$ is $\pi$, as shown in Figure 3(b).

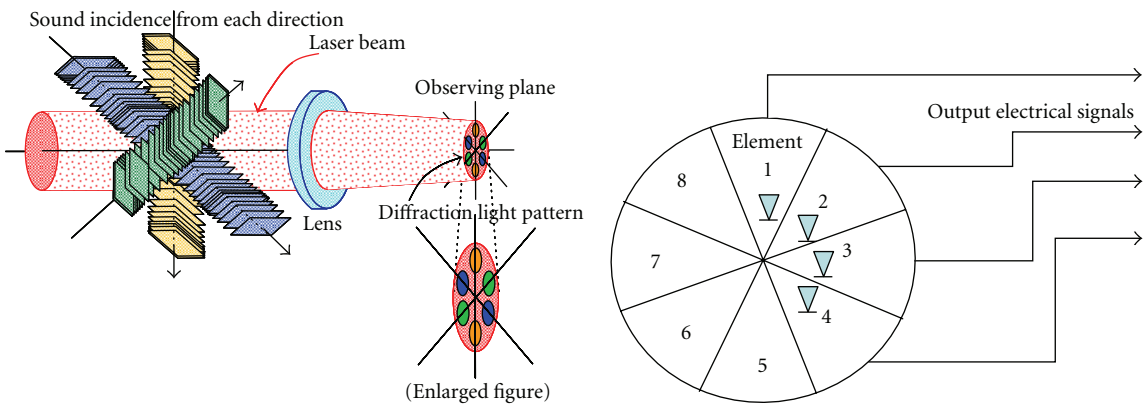
From (1), it is found that the optical signal intensity is theoretically in proportion to the frequency of sound wave. In application to sound or noise measurement, the frequency response of the optophone system is made flat over the whole frequency band by an electric signal processing circuit.

If some sounds enter a laser beam from different directions, the diffraction patterns appear at different positions in the observing plane as shown in Figure 4(a). This property can be used to separate sound signals to each incident direction and/or to realize a hand controllable directivity by using a divided multiple photodetector or an optical fiber bundle, as shown in Figure 4(b).




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

Figure 3: Theoretical profiles of diffracted light distribution.




(a) Physical image (b) Control of directivity by multiple photo detector

Figure 4: Relation between sound incident direction and diffraction light pattern.

## 3. Property and Merits

Based on the above principle, the various types of optophone can be constructed, which directly detect acoustic waves by a laser light beam and have many advantages as follows [6, 7].

(1) A sensing light beam of the optophone never disturbs sound field and also flow of air.

(2) A wide frequency response from audio to ultrasonic bands is realized.

(3) The sound sensor is not destroyed by ultrahigh sound pressure or shockwaves and even can measure such special phenomena.

(4) The optophone is applicable to sound measurements under such special conditions as the high electric and/or magnetic fields, where the conventional microphone cannot be applied to. It can also measure sounds in the airtight chamber, if an optical small window exists.

(5) Any lasers from visible-to-near infrared wavelengths can be used. In accordance with practical needs, the visible or invisible laser microphone can be constructed.

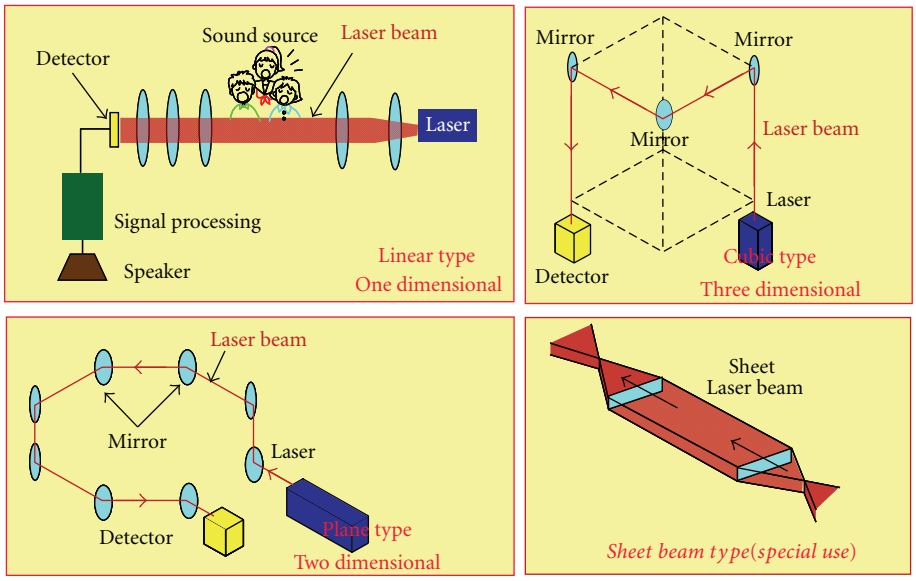
(6) The sound receiving part or laser beam of the optophone can be constructed in one to three dimensions, by which we can offer various directivities and sizes from a compact one to an ultralarge antenna type or a macroscopic phone (or macrophone), as shown in Figures 5(a) and 5(b).

(7) The sound signal can be optically amplified and trans-mitted by an optical fiber without the disturbance of electromagnetic noise.

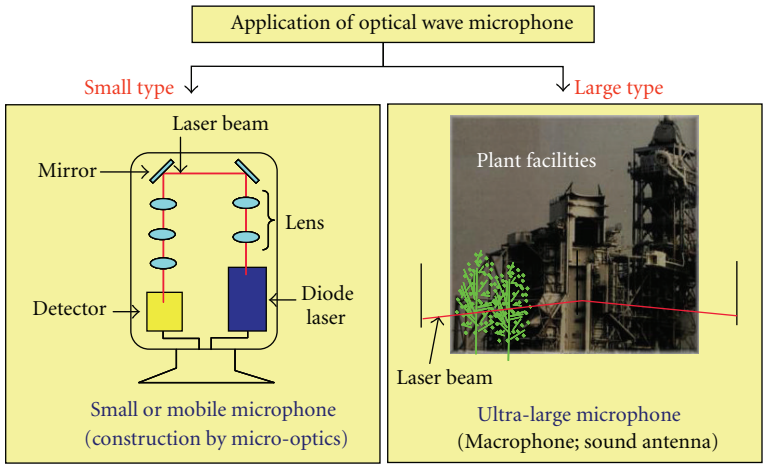
## 4. Fundamental Experiments and Results

The fundamental characteristics of the optophone have been experimentally examined, main results of which are shortly summarized below as (1) linearity of optophone signal for sound pressure and laser power, (2) frequency property, (3) directivity, (4) examination of optical information processing system, (5) basic study of sound antenna using laser beam, and (6) visualization of sound field by laser beam microphone with computerized tomography [8–16]. Finally, as an example of applications, the studies of sound measurement in jet flow are described in the next chapter [17–20].

The abstract of experimental apparatus set up in an anechoic box is shown in Figure 6. This equipment was arranged so that the principle figure shown in Figure 2 was realized, and it was used to examine the fundamental property.




(a) Fundamental structures of optical wave microphone




(b) Small type and sound monitor for a wide area

Figure 5: Various types of optical wave microphone for application.

In Figure 6, a diode laser (670 nm) of 6 mW is used, and the spot size at the interaction point of a laser beam and a sound wave is about 2 mm. When the incident laser beam crosses a sound wave, the diffracted light wave is generated and propagates with or within the penetrating beam, and passes through the Fourier optical system, and finally reaches an optical detector. The sound waves are emitted from a speaker or an ultrasonic transducer. In the receiving optics, the Fourier optical system composed of three lenses is adopted. The detector is a photodiode of 0.8 mm diameter. The sensitivity is 0.43 A/W (at 633 nm), and the noise equivalent power is $6.8 \times 10^{-16}$ W/Hz$^{1/2}$. The output signal from the photodiode is amplified, input into, and analyzed in a digital oscilloscope and a computer system. The sound pressure level is monitored by an electrostatic microphone system. If the sound pressure is larger than about 80 dB, a single tone or a music sound detected or recorded by the optophone can be reproduced by a small home stereo system [8]. Some other apparatuses similar to Figure 6 were also used for other various experiments having different purposes.

By these systems, the fundamental characteristics were experimentally examined, as described in the following sections.

*4.1. Linearity of Optophone Signal for Sound Pressure and Laser Power.* In order to examine the relation between the sound pressure and the diffraction signal intensity, experiment was carried out, changing the sound pressure. The experimental result is indicated in Figure 7. The optical signal intensity is found to be linearly proportional to the sound pressure under the present condition less than 110 dB. As the interaction between light beam and sound wave is extremely small, the sound pressure higher than it can

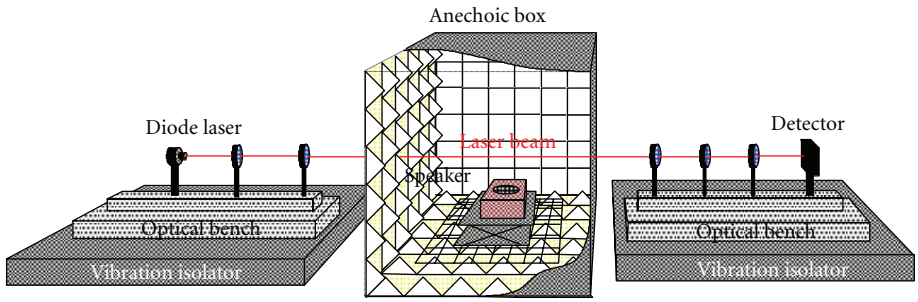



Figure 6: An example of experimental apparatus for fundamental study.

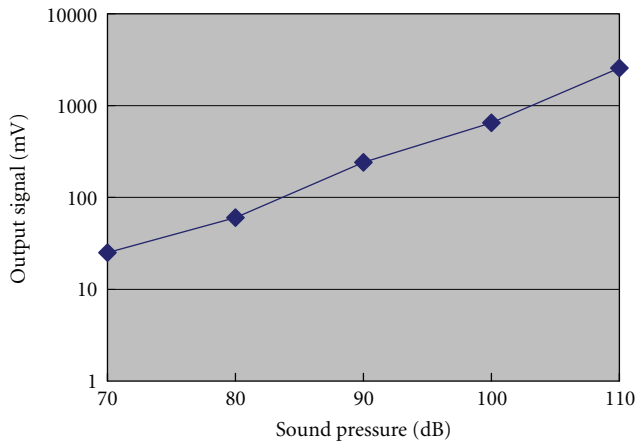



Figure 7: Linearity of signal for sound pressure.

be measured. Furthermore, the relation between the signal intensity and the laser power less than 28 mW is examined for sound pressure of 90 dB, and the result is shown in Figure 8, where the unit of horizontal axis is percentage. It is found that the signal intensity is proportional to the laser power lower than 28 mW.

*4.2. Frequency Property.* Figure 9 shows examples of time traces of optical signals at the observing plane, measured in the apparatus shown in Figure 6, where the frequencies of sound are 200, 500, 1 k, 5 k, and 10 kHz, respectively, and the sound pressure is changed from 75 to 100 dB for each frequency.

Relation between the sound frequency and the optical signal intensity for each sound pressure is plotted on Figure 10, where the solid and dotted lines indicate the approximated curves. The amplitude of output signal is linearly proportional to the sound frequency, which is consistent with the prediction by the theoretical analysis [8].

*4.3. Directivity.* The property of directivities in two planes vertical and parallel to the optical axis of laser beam propagation was measured by the setup shown in Figure 11 [7]. The results are shown in Figures 12(a) and 12(b). The directivity property in the vertical plane for each frequency (200 Hz to 10 kHz) is very similar to each other, and the full angle of half maximum (FAHM) of directivity is about 120° as shown in Figure 12(a). On the other hand, the directivity in the parallel plane for each frequency is different from each other. The directivity for low frequency is relatively broad. The FAHM of directivity is about 90° for 10 kHz and is larger than 90° for other lower frequency, as shown in Figure 12(b) [8].

*4.4. Examination of Optical Information Processing System.* In the optophone with no diaphragm, the optical signal processing or the Fourier optical system is used to detect extremely weak diffraction light generated by the phase modulation effect of sound waves crossing the laser beam in air. The relation between the incident position of sound wave in the Fourier optical system composed of five lenses and the electrical signal intensity outputted from a photodiode was experimentally examined [10].

The experimental results were theoretically investigated by the phase modulation theory and the optical information theory, and the important conditions for the receiving optics were obtained. These are useful for the microphone system design.

Figure 13 shows the experimental setup, where the region (A)~(F) shows the sound incident regions, and a sound transmitter of 20 kHz is set under the laser beam. A diode laser (670 nm) of 6 mW is used as a light source. The detector is a photodiode of 0.8 mm diameter.

The abstract of laser beam transmission is shown in Figure 14. In this figure, the sound incident regions names

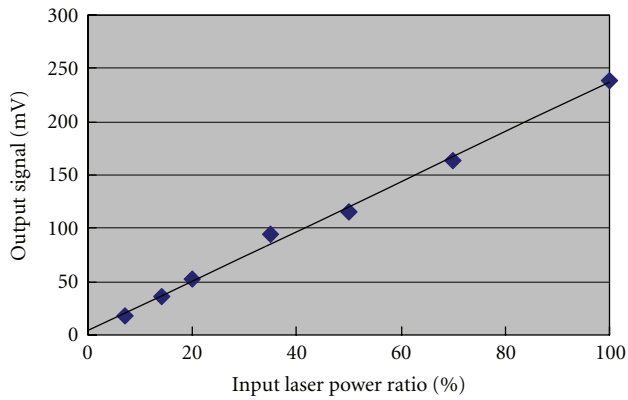



Figure 8: Linearity of signal for laser power.

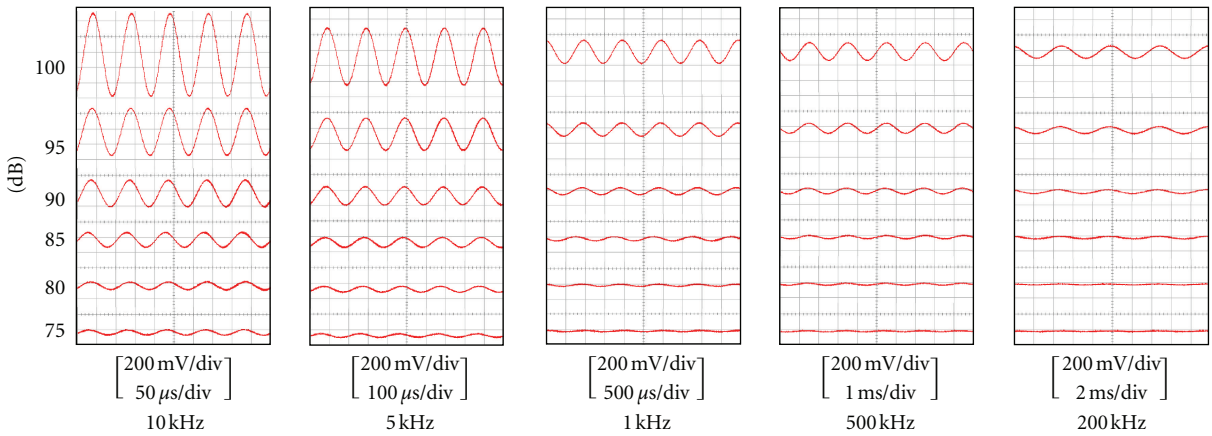



Figure 9: Time profiles of output signal for each frequency.

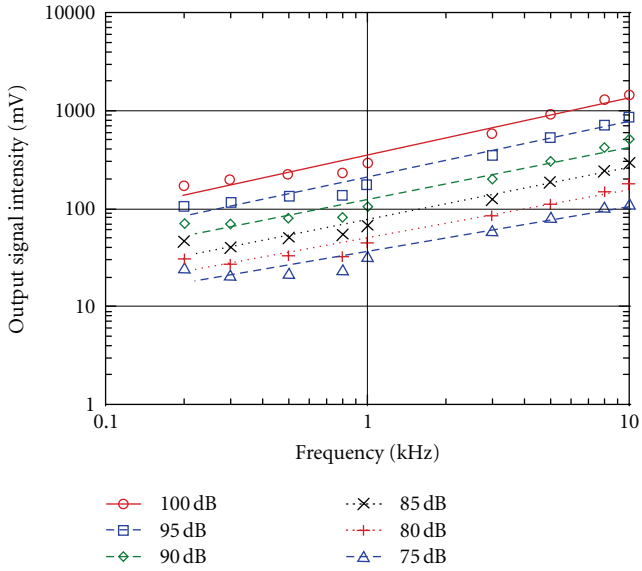



Figure 10: Frequency property.

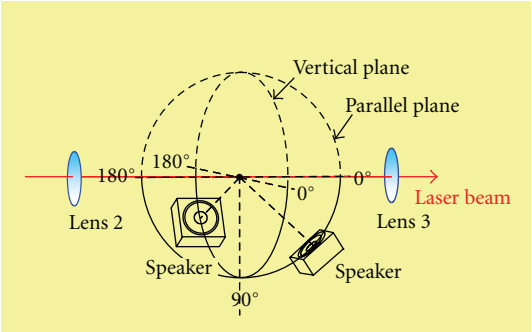



Figure 11: Experimental setup for measurement of directivity in the vertical and parallel planes.

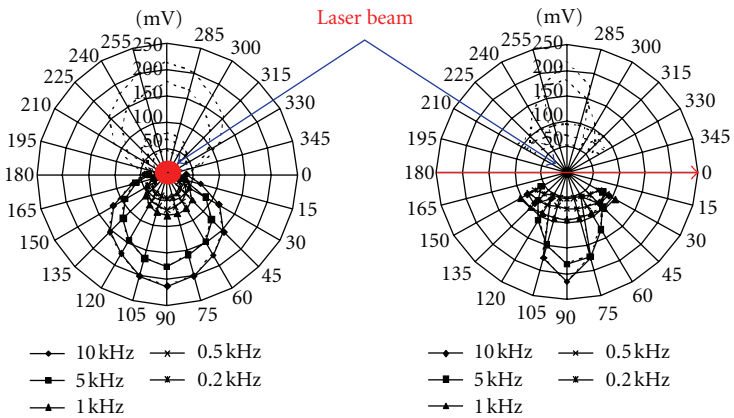



Figure 12: Directivity in the vertical and horizontal planes. (a) Directivity in the vertical plane perpendicular to laser beam axis, (b) directivity in the horizontal plane involving laser beam axis.

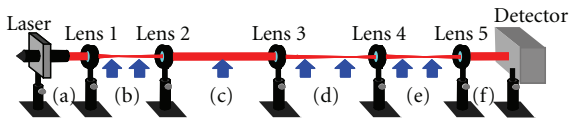



Figure 13: Experimental setup for optical information processing research.

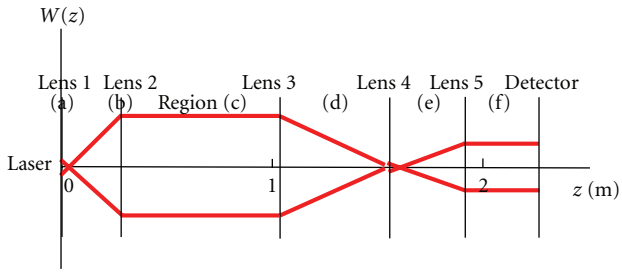



Figure 14: Laser beam transmission.

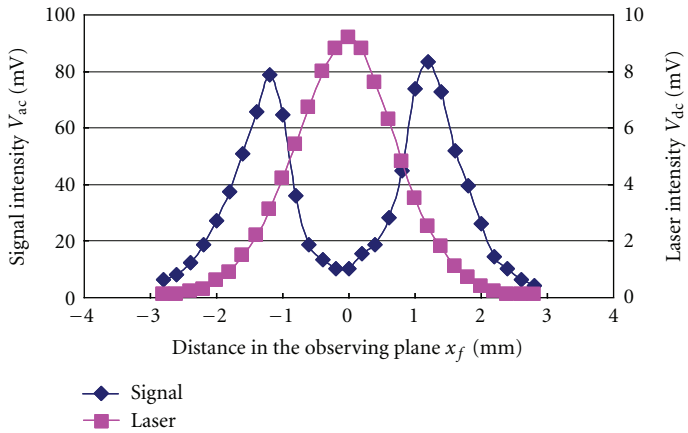



Figure 15: An example of spatial profile of diffraction light measured in the observing plane.

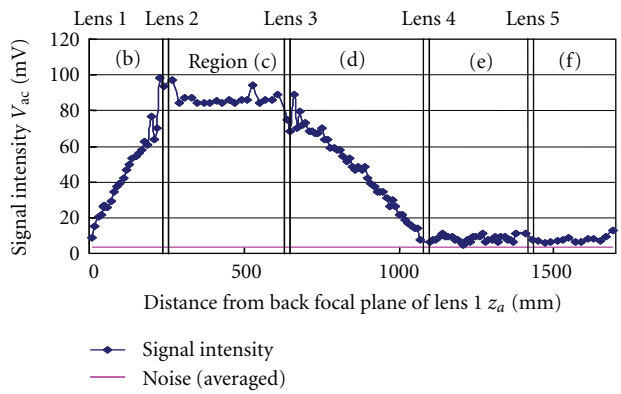



Figure 16: Change of signal intensity for each sound incident position.

of (A)–(F) are also indicated. The ordinate axis of arbitrary unit is linearly proportional to the width of laser beam. The laser beam diameter at the region (C) is 4 mm.

Figure 15 shows an example of spatial profiles of the diffraction light, and the power distribution of laser beam in the observing plane is also indicated. The diffraction light profile measured has two peaks on left and right sides as predicted by the theory. The important experimental result in this experiment is shown in Figure 16. It shows the change of signal intensity for each sound incident position. The maximum intensity is obtained at the region (C). The result is consistently understood by using the theory described at Chapter 2, which shows that the maximum signal is obtained when a sound crosses the laser beam at the spatial position that satisfies the relation of optical Fourier transform to the observing plane. The region (C) is used as a sound sensing part of the optophone system [11].

*4.5. Basic Study of Sound Antenna Using Laser Beam.* The receiving property (directivity, frequency property, signal amplification, etc.) of the optophone can be controlled by changing the laser beam antenna construction. In this study, directivity of double laser beam antenna reflected by a roof mirror was experimentally examined [12]. The experimental apparatus is shown in Figure 17. In this figure, a speaker can be rotated around the double laser beams. The other optical and detection system is similar to one of Section 4.4.

The change of signal intensity by increasing the gap between two laser beams, as shown in Figure 17, was measured. A sound of 10 kHz was injected from horizontal direction in the plane including two laser beams. The photo detector was set at the best spatial position, where the maximum signal intensity was obtained for horizontal sound incidence, in the observing plane. The result is shown in Figure 18. The signal intensity becomes the maximum every half sound-wavelength distance, and the value is nearly twice one of a single laser beam. The signal lights diffracted from two intersection points between the reciprocating laser beam and a sound are found to be linearly added. This result is in agreement with the theoretical prediction of weak interaction between light and sound.

On the other hand, Figure 19 shows the directivity of this two laser beam antennas made by roof mirror reflection. In this case, the photo detector was set at the spatial point where the signal became maximum value for each sound incident direction, as shown in Figure 4(a). The error at angle from 120 to 150 degree was caused by the reflection of sound from surrounding objects [12]. The knowledge about sound

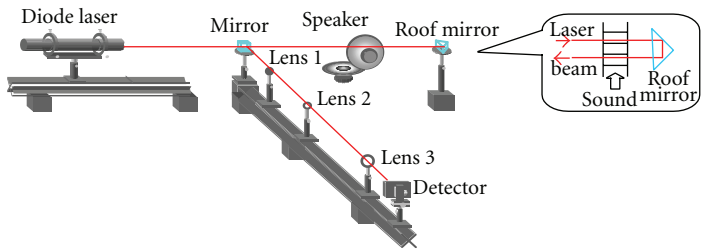



Figure 17: Experimental apparatus for sound antenna study.

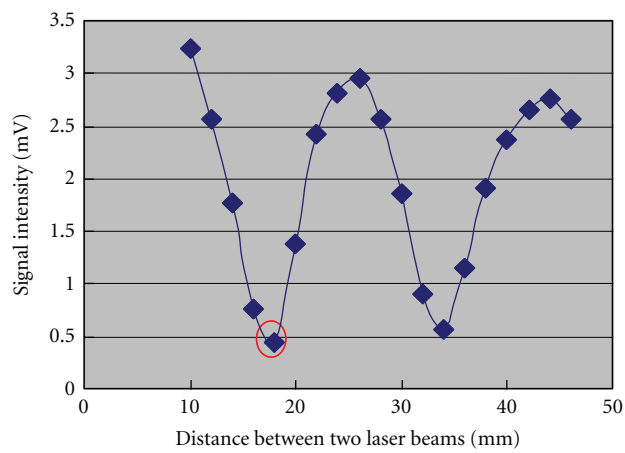



Figure 18: Change of signal intensity to the distance between two laser beams ($f = 10$ kHz).

antenna using laser beam, obtained in the study carried out so far, is not enough, and the establishment of the synthetic design guide for making any laser beam antenna is needed for general applications in various fields.

*4.6. Visualization of Sound Field by Laser Beam Microphone with Computerized Tomography.* The optophone is here called as the laser beam microphone, because it is used as a long laser beam sensor in this theme. As the ultrasmall light modulation by the sound field is integrated along the laser beam path, the laser beam microphone has a possibility to realize a sound field visualization method by combining it with a computerized tomography (CT) method [13]. The final objective of this study is to establish the laser beam microphone coupled with CT method, which can reconstruct and visualize the amplitude and phase distributions of a complex sound field. In this feasibility study, as a first stage of research, the sound field with almost uniform phase distribution in the cross-section including the probing laser beam was chosen as the subject of measurements, and the experiment to verify the possibility of the method for visualization of only the amplitude distribution of sound field was carried out [14].

The diffraction signals due to the sound wave with frequency of 20 kHz are measured, and the reconstruction of the sound field is examined by means of CT method, whose results are compared with those measured by an electrostatic microphone.

Figure 20 shows the image of rotation and r-direction scanning operations of laser beam in a sound field to get data for CT reconstruction. The experimental setup is shown in Figure 21, in which a speaker is rotated and scanned instead of moving the large laser system. The experimental results are shown in Figures 22(a)–22(c). Figure 22(b) shows a reconstructed distribution of the sound field at the $x$-$y$ plane by the laser beam microphone with CT method and is similar to Figure 22(a) measured by an electrostatic microphone. Profiles of the sound pressure distribution along the $y$ direction with $x = z = 0$ mm, obtained by both methods, are shown in Figure 22(c) in which circles denote projection data obtained by the laser beam microphone with CT and squares denote values by the electrostatic microphone. The solid line denotes the CT profile. The two profiles are roughly in agreement with each other [14].

Furthermore, experiments using two ultrasonic transducers (20 kHz) were carried out [15]. An example of results is shown in Figures 23(a) and 23(b), in which the same voltage is applied to two transducers. It is found to be consistent with one measured by an electrostatic microphone.

From these results, it was concluded that the laser beam microphone with CT method is useful to visualize the sound field.

This method was also applied to measurement of electrical discharge sounds generated from an ozone generator [16].

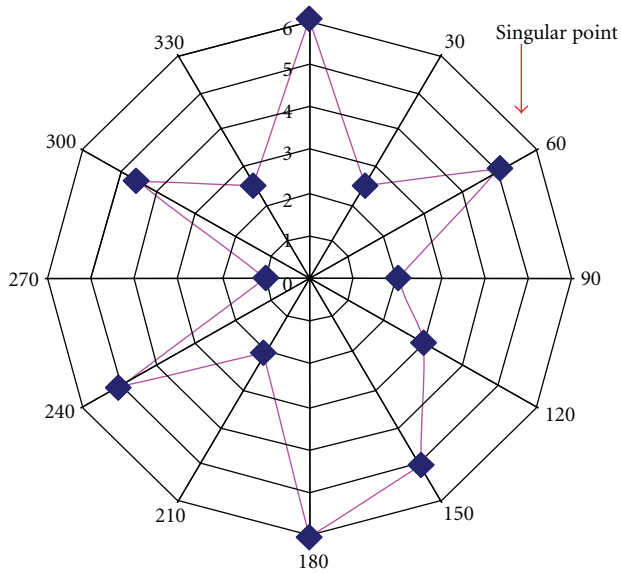



Figure 19: Measured directivity for 20 kHz (distance between two laser beams: 25.5 mm).

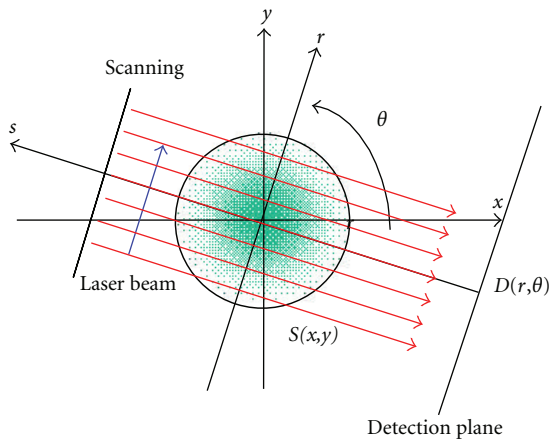



Figure 20: Rotation and scanning operation for CT reconstruction.

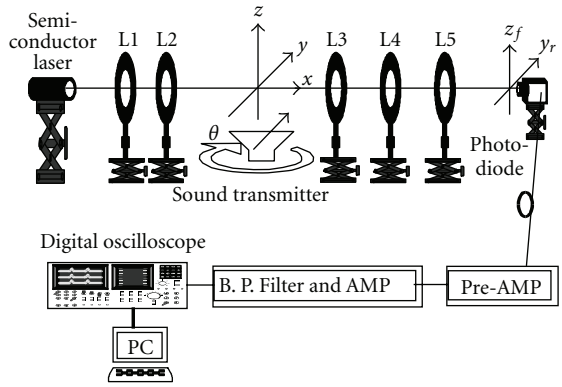
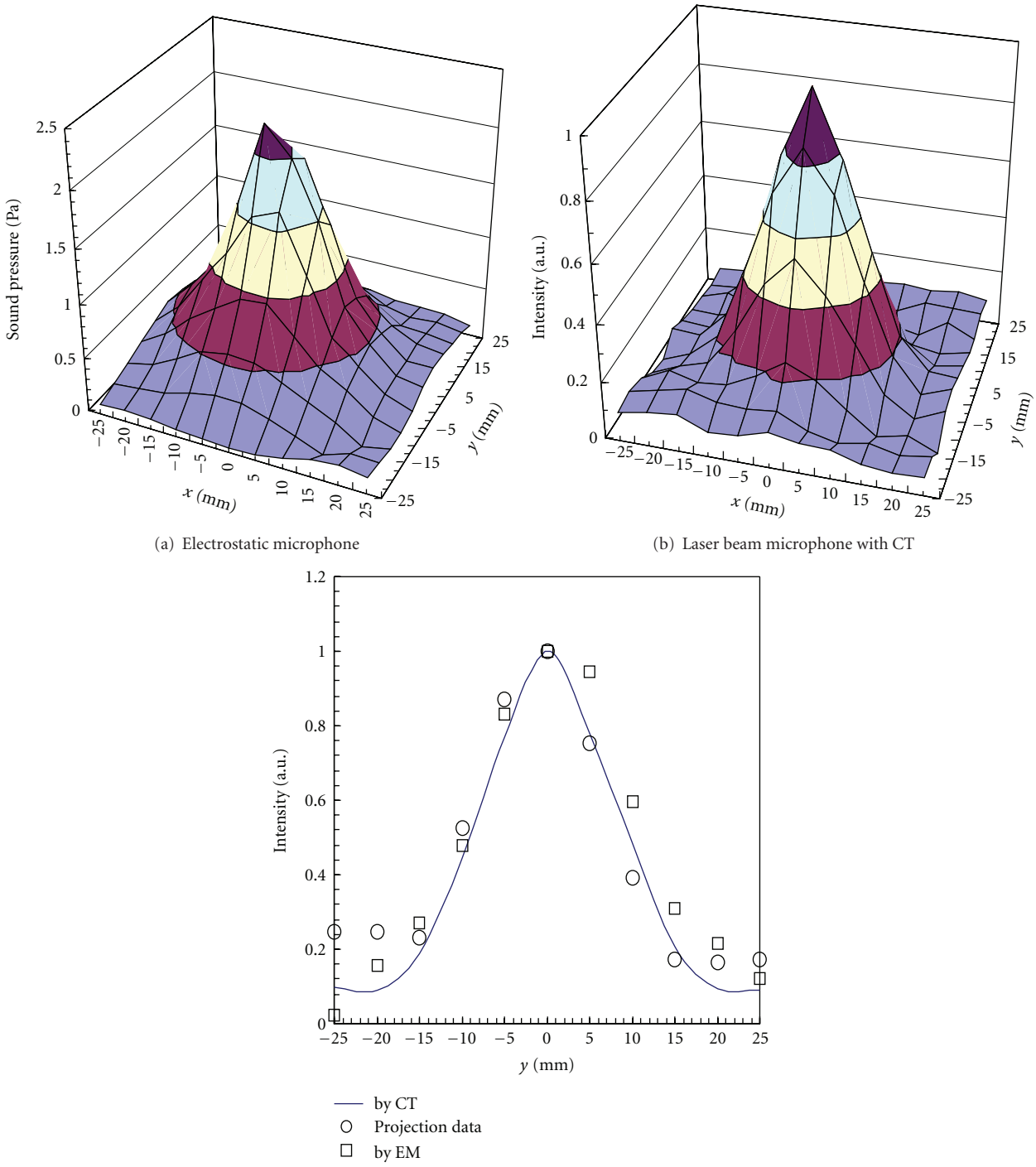



Figure 21: Experimental setup.




(a) Electrostatic microphone

(b) Laser beam microphone with CT

(c) Comparison

Figure 22: Comparison of measured results.

## 5. Application to Sound and Noise Measurement in Jet Flow

*5.1. Influence of Background Flow Noise to Sound Measurement with Optophone.* By using this method, it is expected that sounds generated in a jet flow can be measured without any disturbance [17–20].

The possibility of application of the optophone to the jet flow system was experimentally investigated, before applying it to measurement of sounds naturally generated in a jet flow [17]. Figure 24 shows the experimental setup. The measurement optical system consists of a diode laser (635 nm; 10 mW), laser beam transmission part (lens 1-lens 2), optical information processing part (lens 3–lens 5), and

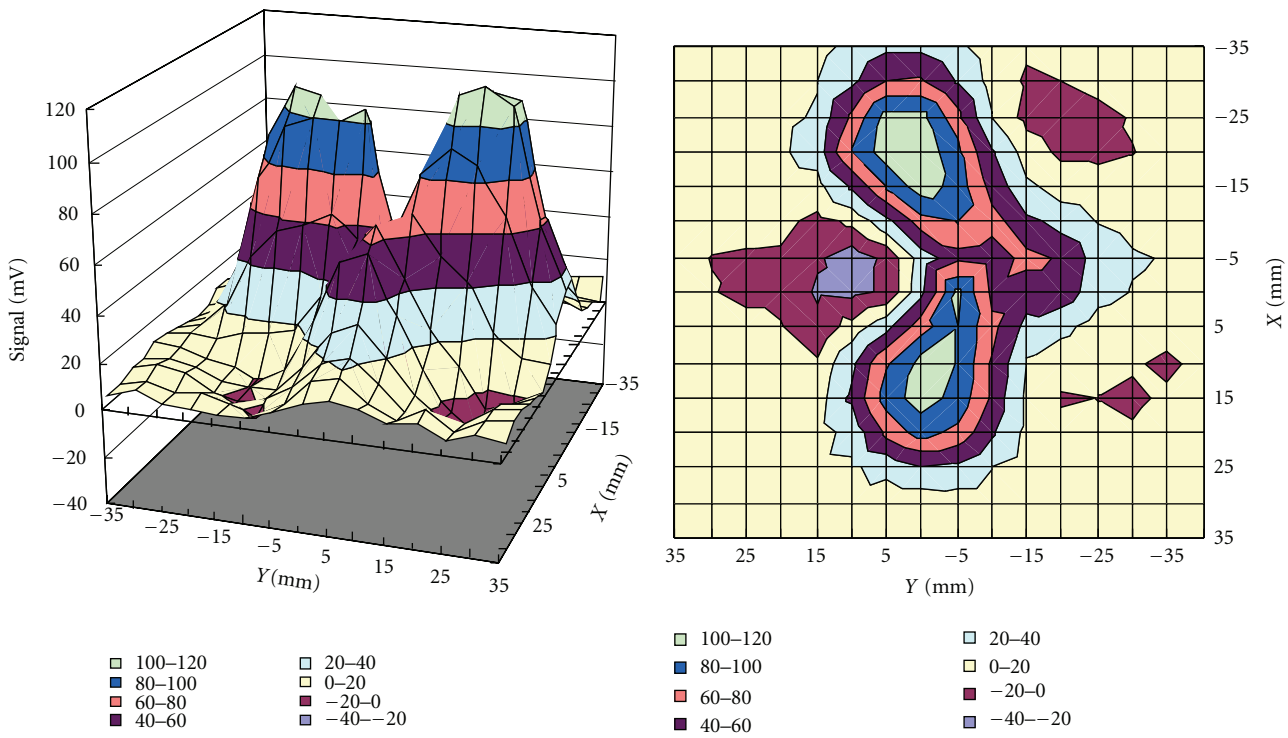



Figure 23: Measurement of sound field emitted from two transducers.

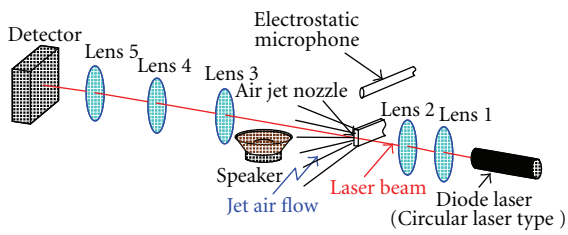



Figure 24: Experimental setup for sound detection in jet flow.

an optical detector (photodiode). The focal length is 50 mm (lens 1), 150 mm (lens 2), 500 mm (lens 3), 10 mm (lens 4), and 300 mm (lens 5), respectively. The distance between lens 2 and lens 3 was 500 mm. This region is used as a sound detection part. The radius of spot size between lens 2 and lens 3 is 2.2 mm. The radius of laser beam at the observing plane is 1.8 mm. These optical devices are installed on an optical rail with air dampers. Furthermore, these are installed on the jack and can be perpendicularly and horizontally scanned. The width of the nozzle head generating a jet flow is 5 mm × 20 mm, as shown in Figure 24.

The frequency characteristic of the optophone is made into the flat one by the optical detection circuit. The electric signal outputted from the detector circuit is amplified and analyzed with a FFT analyzer or a digital storage scope.

As it was difficult to theoretically estimate the influence of the vibration or fluctuation of optical system by the jet flow system, the possibility was investigated by experiment entering a test sound and measuring it. And the influence of the background noise in flow of air on the sound measurement by the optophone was experimentally estimated.

In the experiment, a test sound of 100 dB and 10 kHz is transmitted from a speaker set up near the jet flow. The laser beam passes through the acoustic wave propagating region and the jet flow and reaches to a detector. The Mach number $M$ is changed from 0 to 0.5. By these processes, the measurement possibility is investigated.

An example of frequency spectra measured by the optophone is shown in Figure 25, in which (a) $M = 0$, (b) $M = 0.1$, (c) $M = 0.25$, (d) $M = 0.5$, and the peak point of 10 kHz is the test sound signal. Figure 26 shows the relationship between Mach number and SN ratio. It is found that the SN ratio for the sound level of 100 dB is about 40 dB at $M = 0.1$ and it becomes nearly 1 at $M = 0.5$ for the present apparatus and experimental condition.

*5.2. Application to Cavity Tone Measurement.* Based on the basic experimental result described above, the optophone

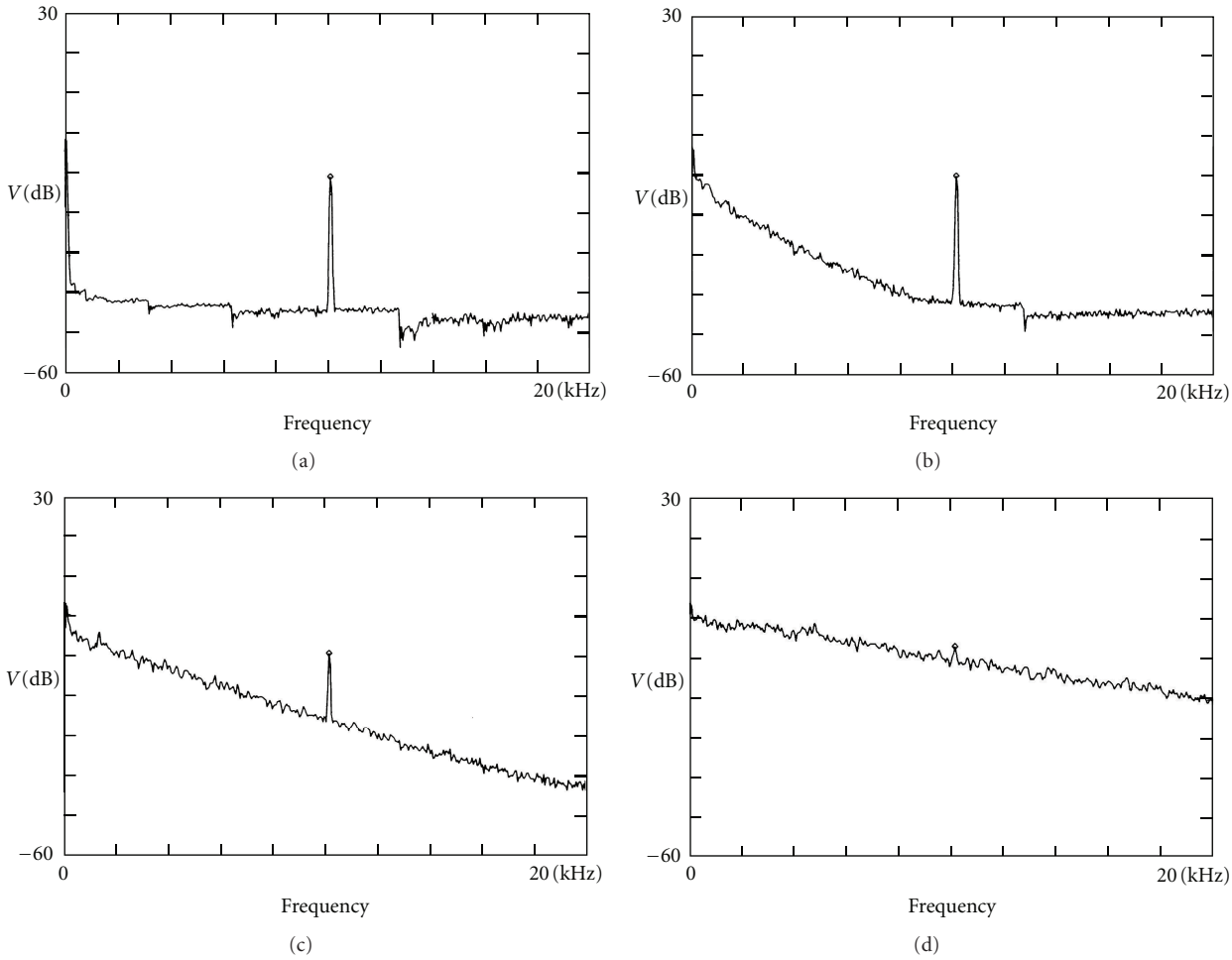



Figure 25: Frequency spectra of speaker sound in air jet flow. (a) $M = 0$, (b) $M = 0.1$, (c) $M = 0.25$, (d) $M = 0.5$.

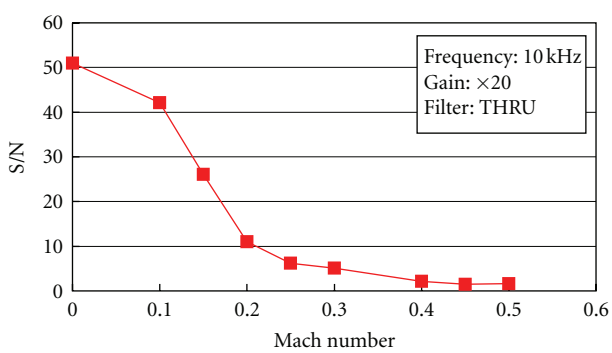



Figure 26: Relationship between Mach number and SNR.

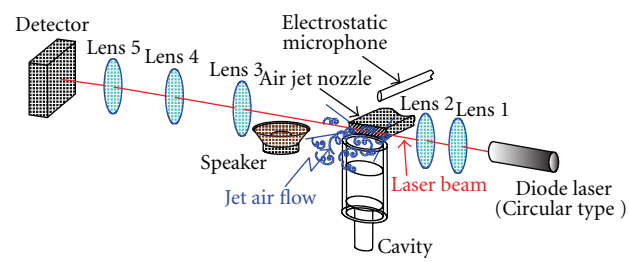



Figure 27: Experimental setup with cavity.

was applied to measurement of a cavity tone generated in the jet flow. Figure 27 shows the experimental setup, in which the cavity (diameter: 30 mm, depth: variable) is installed at the tip of the nozzle head. The generated cavity sound is measured with the optophone. Moreover, the spatial distribution of cavity tone is obtained by scanning the optophone system to axial direction and compared with one measured before by an electrostatic microphone with a probe tube.

The flow velocity is set at $M = 0.3$, and the cavity depth is 17.5 mm. The vertical distance between laser beam and cavity head is about 5 mm. The optophone system is scanned to horizontal or axial direction from 5 mm to 75 mm, where the axial original point is at the nozzle head.

The frequency spectra obtained at each measurement position are shown in Figure 28. From these data, the relationship between distance and signal strength for the main frequency is obtained and shown in Figure 29, in which the signal of 3225 Hz measured before with the probe tube microphone is also shown for comparison [17].

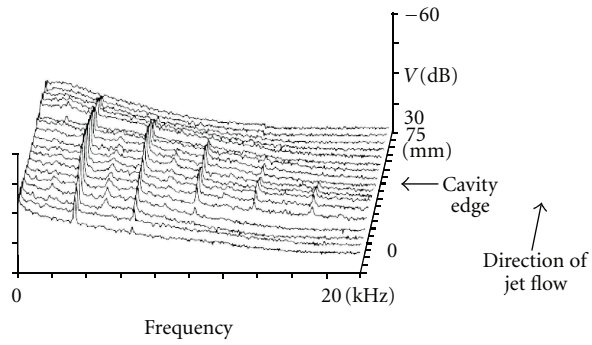



Figure 28: Frequency spectrum of cavity tone measured by optophone.

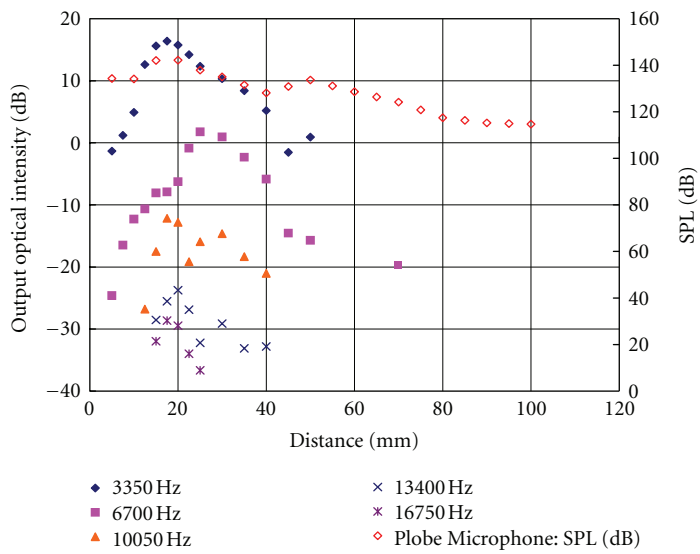



Figure 29: Axial distribution of signal intensity for each frequency.

Although the present argument is still based on the qualitative estimation, the characteristic tendency for signal intensity to become maximum on the cavity head part is found, which agrees with the result obtained before by an electrostatic probe tube. In this research, it is verified that the cavity sound generated in a jet flow can be measured by the optophone without disturbing the jet flow. However, as the signal intensity is smaller in a downstream region, detection sensitivity is not enough with the present system. The improvement of sensitivity and quantitative estimation are needed.

*5.3. Application to Screech Jet Noise Measurement.* The optophone was applied to measurement of screech jet noise exhausted from a nozzle with a hard reflecting plate [20]. The standing wave in the near field of the screech jet with a hard plate works on the jet flow as the forcing wave according to the proper location of a reflecting plate. The reflector position also changes the map of the near field. Intensity maps of the screech tone, which indicate the states of propagation to the axial and radial directions in the jet flow, had not been explored. In this application study, acoustic characteristics in the near field of the screech tone were studied by using the optophone, which could separately measure the sound propagating for both vertical and horizontal directions to the jet axis.

Figure 30 shows the optophone system for measuring the near field of jet noise. The optophone system is scanned to $x$ and $y$-directions, respectively. The nozzle used in the experiment is a tube nozzle extended with a straight length of 46 mm from a normal nozzle exit to the downstream, and its inner diameter is 10 mm. A hard acrylic reflecting plate is set on the circumference of the nozzle and is moved to upstream of the nozzle exit. It has a thickness of 5 mm and a diameter of 200 mm, which is adequate in canceling the screech. On the basis of the acoustic measurement of the far field, the positions of the hard reflecting plate of $L = 10$ mm and 20 mm are chosen, which show the maximum and minimum screech tone level respectively. The results are compared with those of the experiment with no plate.

As an example of results measured by the optophone, contours of laser signal intensity at a screech frequency of 11 kHz for $L = 10$ mm are shown in Figure 31. From Figure 31(a) of vertical mode, the strongest sound source is found to be

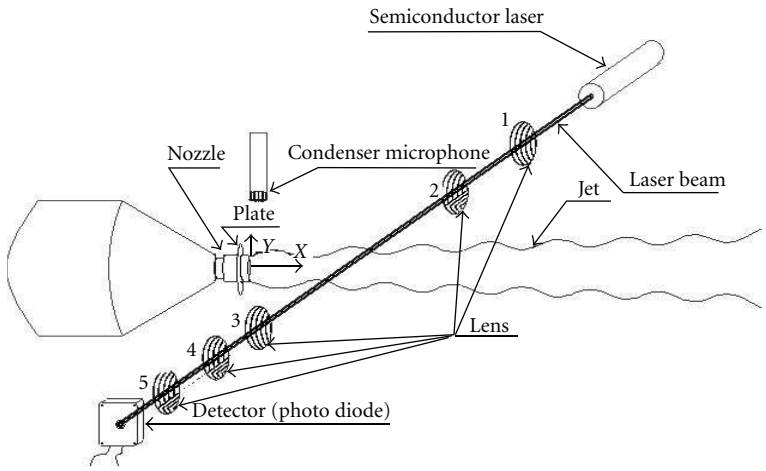
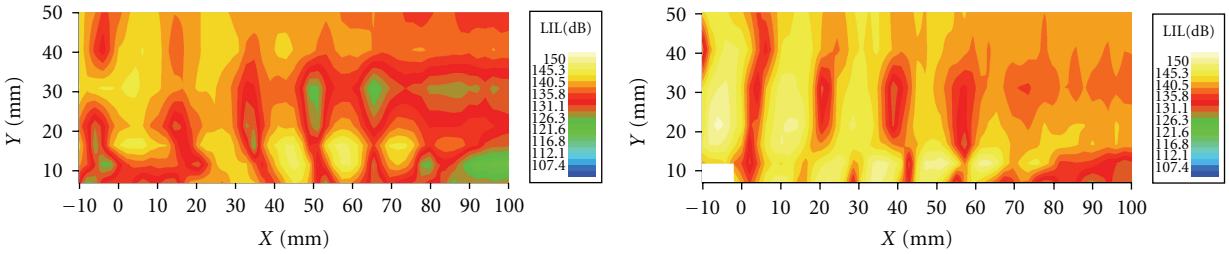



Figure 30: Experimental apparatus of the jet and optophone system.




(a) The vertical mode

(b) The horizontal mode

Figure 31: Vertical and horizontal modes contours in the near field ($L = 10$ mm, $f = 11$ kHz).

located at the position near the 3rd and 4th shock waves, which is similar to the results of the no plate. The screech tone is intensified upstream by the reflector, and is decreased downstream. The sound generated influences on the jet structure.

By combining these measurements using the optophone, it is totally shown the following. (1) The main noise source of the screech jet is placed near the 3rd and 4th shock locations, and its location is not influenced to a great extent by the reflector. (2) Screech tone does not have an influence on the spacing of the shock waves, but the maximum screech tone influences the jet and collapses the shock waves after the 5th shock wave. (3) The standing wave in the near field of the screech jet with the reflector has two types: one is the standing wave between the hydrodynamic pressure fluctuation propagating jet downstream and the sound pressure propagating upstream, and the other is the standing wave by the difference between the wavelength of the sound wave and the wavelength of the standing wave at the place close to the jet.

*5.4. Problems for Practical Uses in General Acoustic Engineering.* In the preceding chapters, the optophone was proposed and the fundamental studies were shortly described. Figure 32 shows the extent of general sound utilization in life and the status of the present research development of the optophone. In this figure, the line of 2nd stage roughly shows the present status, which shows that the sound from 300 Hz to 100 kHz can be detected with SNR of 2-3 by the optophone. The measurable lowest frequency is limited by the high-pass filter of 300 Hz used to cut off noises, and the lowest sound pressure is limited by background noise level of about 50–60 dB in the experimental room. The causes of noise are not clear in the present experiment. It is needed to locate noise sources and to improve sensitivity or SN ratio for wide industrial and scientific applications [7].

## 6. Future Technology

In this paper, the laser light is used as a light source of optophone. If the general incoherent light or semicoherent light can be used, which now needs to be experimentally verified, there is a possibility that more important future technology can be obtained. Figure 33 shows the classification of the optophone and an image of future technology proposed by authors, in which an image microphone is still an imaginary machine but is a novel and powerful technique to get the sound information distributed in a wide field by using an optical image sensor or an electronic camera technique [6].

## 7. Conclusion

The development of the optophone with no diaphragm, which is a novel sound detection method based on the wave

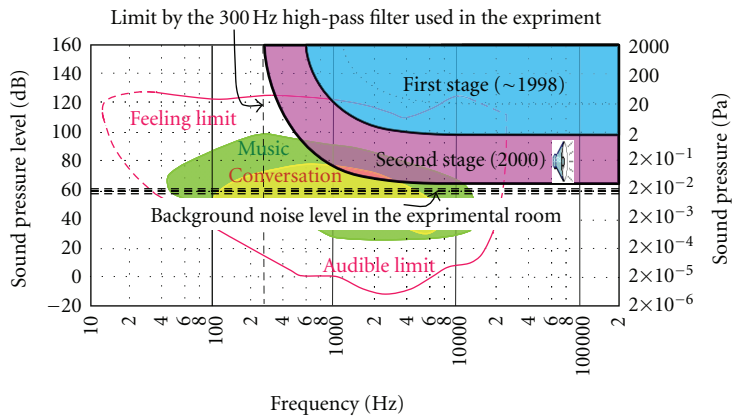



Figure 32: Extent of general sound utilization and present experimental region.

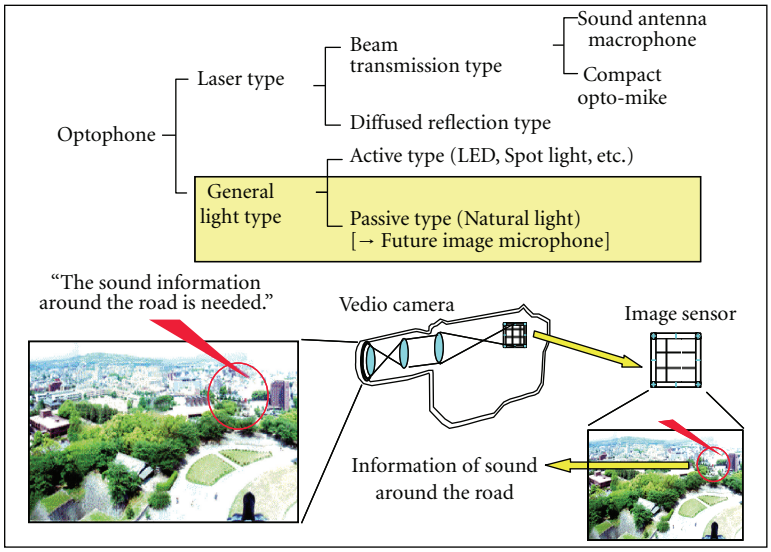



Figure 33: Classification of optophone and future technology proposed by authors.

optics, is shortly reviewed. The theory, merits, hardware, and fundamental property of the optophone and the basic experiments carried out so far are introduced. The present most important problem of the optophone is the improvement of SNR to realize the detection of the low sound pressure level. Further the researches for developing this method are continued.

It is especially desired that this method, which has been limited to a small research group and a narrow field in Japan, will become to be widely used or studied by worldwide researchers engaged in acoustic engineering.

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## References

[1] A. Korpel, *Acousto-Optics*, Marcel Dekker, 2nd edition, 1997.

[2] D. E. Evans, M. von Hellermann, and E. Holzhauer, "Fourier optics approach to far forward scattering and related refractive index phenomena in laboratory plasmas," *Plasma Physics*, vol. 24, no. 7, pp. 819–834, 1982.

[3] Y. Sonoda, Y. Suetsugu, K. Muraoka, and M. Akazaki, "Applications of the Fraunhofer-diffraction method for plasma-wave measurements," *Plasma Physics*, vol. 25, no. 10, pp. 1113–1132, 1983.

[4] Y. Sonoda and M. Akazaki, "Measurement of low-frequency ultrasonic waves by Fraunhofer diffraction," *Japanese Journal of Applied Physics*, vol. 33, no. 5B, pp. 3110–3114, 1994.

[5] Y. Sonoda, "Direct detection of acoustic waves by laser light diffraction and proposals of the optophone," in *Proceedings of the 16th International Congress on Acoustics and 135th Meeting of the Acoustical Society of America*, vol. 1, pp. 427–428, 1996.

[6] Y. Sonoda, "Method to hear sound by light—development of optical wave microphone with no-diaphragm," *Optical Alliance*, vol. 16, no. 7, pp. 32–39, 2006 (Japanese).

[7] Y. Sonoda, "Development of optical wave microphone—direct detection of sound (from audible to ultrasonic bands) by Light," *Ultrasonic Technology*, vol. 23, no. 5, pp. 48–54, 2011 (Japanese).

[8] K. Tanaka, G. Nogami, and Y. Sonoda, "Measurement of audible acoustic wave by laser light," *Transactions of The Institute of Electrical Engineers of Japan*, vol. 122, pp. 362–368, 2002 (Japanese).

[9] T. Sakoda and Y. Sonoda, "Transmission and detection of light diffraction signal by low-frequency ultrasonic wave," *Japanese Journal of Applied Physics*, vol. 42, no. 9A, pp. 5821–5825, 2003.

[10] T. Sakoda and Y. Sonoda, "Measurement of low-frequency ultrasonic wave using an acoustic fiber sensor," *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, vol. 53, no. 4, pp. 761–767, 2006.

[11] Y. Sonoda, "Investigation of optical system for direct detection of audio-wave by optical Fourier transform," *The Journal of The Acoustical Society of Japan*, vol. 62, pp. 571–579, 2006 (Japanese).

[12] Y. Sonoda, Y. Nakazono, Y. Ohuchi, and T. Samatsu, "Construction of laser beam antenna and sound receiving characteristics of optical wave microphone," *Bulletin of School of Engineering, Kyushu Tokai University*, vol. 34, pp. 97–98, 2007 (Japanese).

[13] Y. Ikeda, M. Goto, N. Okamoto, T. Takizawa, Y. Oikawa, and Y. Yamasaki, "A measurement of reproducible sound field with laser computed tomography," *The Journal of the Acoustical Society of Japan*, vol. 62, pp. 491–499, 2006 (Japanese).

[14] T. Sakoda and Y. Sonoda, "Visualization of sound field with uniform phase distribution using laser beam microphone coupled with computerized tomography method," *Acoustical Science and Technology*, vol. 29, no. 4, pp. 295–299, 2008.

[15] Y. Sonoda, K. Sirouzu, and T. Sakoda, "Visualization of sound field emitted from two speakers by laser beam microphone CT method," *Bulletin of School of Engineering, Kyushu Tokai University*, vol. 34, pp. 95–96, 2007 (Japanese).

[16] T. Nakamiya, Y. Iwasaki, F. Mitsugi et al., "Investigation of electric discharge sound in atmospheric pressure plasma using optical wave microphone," *Journal of Advanced Oxidation Technologies*, vol. 14, no. 1, pp. 63–70, 2011.

[17] Y. Sonoda, Y. Nakazono, Y. Ohuchi, and T. Samatsu, "Feasibility study for direct detection of acoustic waves in jet flow by laser light diffraction," *Bulletin of School of Engineering, Kyushu Tokai University*, vol. 32, pp. 197–198, 2005 (Japanese).

[18] M. Kosaka, K. Seto, Y. Nakazono, and Y. Sonoda, "Measurement of supersonic jet noise by means of optical wave microphone," *Transactions of the Japan Society of Mechanical Engineers*, vol. 71, no. 5, pp. 186–191, 2005 (Japanese).

[19] Y. Nakazono, Y. Sonoda, and M. Kusuda, "Acoustic characteristics of the optical microphone and its application to aerodynamic noise measurement," *Journal of the Japan Society of Technology Education*, vol. 50, pp. 85–93, 2008 (Japanese).

[20] Y. Nakazono, Y. Sonoda, Y. Ouchi, and Y. Nasu, "Near-field acoustic characteristics of screech jet exhausted from a nozzle ith a hard reflecting plate," *Journal of Visualization*, vol. 11, no. 2, pp. 153–162, 2008.