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# Improvement of laser microphone using self-coupling effect for spherical sound wave detection

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**Abstract**

A laser microphone using the self-coupling effect of laser diodes has a simple optical system, with a wide and flat frequency characteristic. However, due to the structure of the sensor section, detection of spherical sound waves has been difficult until now. In addition, simple miniaturization of the sensor parts of the laser microphone causes a decrease in sensitivity. To address these issues, a laser microphone sensor structure using multiple reflections from a pair of mirrors is considered. By using a multiple reflection sensor, the laser microphone retains sensitivity while achieving the desired miniaturization. When a multiple reflection sensor is used, the sensitivity improves up to approximately seven times, compared to simple miniaturization of the sensor part. When a sound source which generates spherical waves was used for measurement, the sound pressure distribution reconstruction achieved by the multiple reflection type laser microphone was the same as that of a conventional quarter inch sensor condenser microphone. It was found that the multiple reflection type sensor allowed downsizing of the sensor part while still being able to measure spherical sound waves.

Keywords: Acoustic, Laser, Measurement, Miniaturisation

## 1. Introduction

The concept of an optical microphone detecting sound waves using laser light was first put forward by Smeets in 1976 [1]. Since then, various detection principles and structures have been proposed, including applying a Mach-Zehnder interferometer [2, 3], opto-acoustic cells [4, 5], slight diffraction of light by sound waves (Raman-Nath diffraction) [6], and using a small etalon (Fabry – Pérot interferometer) as a sensor head [7, 8].

Optical microphones using the self-coupling effect of laser diodes (LD) [9, 10] detect variations in the air refractive index [11], and exhibit the following advantages.

(1) Sound waves are directly detected by a laser beam, so that a membrane is not required.
(2) The self-coupling effect simplifies the optical system of optical microphones, so that an external photodetector and imaging lens are not needed.
(3) Since the detectable frequency and pressure range are not limited, in principle, wide and flat frequency characteristics can be found from the sub-audible sound band to the supersonic band.

Based on these features, a laser microphone is suitable for sound detection in liquids, in air flows or under explosive atmospheres, and for detecting acoustic noise from factories or power stations.

Because optical microphones need an aspect of length for the detection part, spherical sound wave detection is difficult for them. Therefore, research which focuses on spherical sound waves has not been undertaken to date. In laser microphones, the sensor part is a laser beam just a few cm in length. Therefore laser microphones must be designed on the assumption that the incident sound wave is planar, otherwise erroneous detections will be caused by the difference of sound wave phase between the edge and middle of the laser beam, i.e., the spatial resolution of conventional type laser microphones is low and therefore, miniaturization of the sensor section is necessary, in order to facilitate detection of spherical sound waves.

For address this issue, a new sensor structure is proposed for miniaturization. The laser beam is folded into a one centimetre square area, by using multiple reflections from a pair of mirrors. By using a multiple reflection sensor, the laser microphone retains sensitivity and achieves the miniaturization necessary for spherical sound wave detection.

In this presentation, we first compare the characteristics of the new detection structure with that of conventional laser microphones. Next, to confirm the detection of spherical sound wave, we show experimental results of the new laser microphone type, and compare these with results obtained by a condenser microphone.

## 2. Detection principles

First, the LD self-coupling effect, which is applied in laser microphones, is described. A continuously operating LD is arranged to oppose a reflector. Since part of the scattered light from the target returns to the active layer in the LD, the space from the LD to the reflector becomes an external resonator for the laser light. Because the returned light interferes with the light in the active layer of the LD, output power fluctuation occurs in the laser light a phenomenon referred to as the self-coupling effect of LDs. The advantage of self-coupling sensors is their high level of detectability, even for low reflectivity targets. This high detectability is achieved through amplification of the returned light in the active layer of the LD [12].

Next, the sound detection principle is described. Since a sound wave is a compressional wave of air, its refractive index is proportional to the sound pressure, as described by Elden's equation [13, 14]. The refractive index variation in air $\Delta\eta$ is represented by

$$\Delta\eta = (\eta_0 - 1) \cdot \frac{\Delta P \sin\omega_s t}{P_0} \tag{1}$$

where $\eta_0$ is the refractive index of air at a standard temperature and pressure, $\varDelta P$ is the sound pressure, $\omega_s$ is the angular frequency of the sound wave, and $P_0$ is the standard atmospheric pressure.

When a sound wave uniformly enters the entire external resonator, and the original oscillating wavelength of LD is $\lambda_0$, the laser light wavelength in the external resonator $\lambda$ is described by equation (2).

$$\lambda = \frac{\lambda_0}{(\eta_0 + \Delta\eta)} \tag{2}$$

Based on equation (2), when the sound wave enters the external resonator, the laser light wavelength is slightly changed, with the amount being in inverse proportion to the sound pressure.

In this case, the interfered light intensity is proportional to the phase term, as given by equation (3), where $L$ is the external cavity length, i.e., the distance from the LD to the target [15].

$$\cos\left[\frac{4\pi}{\lambda_0} L(\eta_0 + \varDelta\eta)\right] \tag{3}$$

Equation (3) represents the phase variation by the sound wave. The variation of the refractive index of air by the sound wave is very slight, that is, $\Delta\eta$ is much smaller than π, so therefore, equation (3) can be approximated by the Taylor expansion, as shown in equation (4).

$$\cos\left(\frac{4\pi}{\lambda_0} L\eta_0\right) - \frac{4\pi}{\lambda_0} L\sin\left(\frac{4\pi}{\lambda_0} L\eta_0\right)\varDelta\eta \tag{4}$$

From equation (4), effects by the sound wave appear only in the second term, and the phase of the interfered light is linearly changed by the sound pressure. This phase variation is detected by a built-in photo diode as a light intensity variation, so therefore, a sound wave can be directly detected by a laser beam.

## 3. Detection structure and system

### *3.1. Detection structure using multiple reflections*

A photograph of a new detection structure using multiple reflections is shown in figure 1 (a) and 1 (b). The sound incident plane view of the new structure is shown in figure 1 (a), and the side plane view is shown in figure 1 (b).

A distributed feedback (DFB) LD SHARP GH08360A2A (typical oscillation wavelength 830 nm) was used. The GH08360A2A comes as a 5.6 mm diameter metal package, with a monitor photodiode that detects the signal light inside the package. By using a convex lens (focal length 3 mm), the laser beam becomes a collimated beam of 1 mm. 3M prism sheet PV9110N (maximum reflectance 67 %) was used for reflectors, and Edmund Optics Silver vapour deposition mirrors (maximum reflectance 98 %) were used as a pair of mirrors. A sound insulator (ABS resin, thickness 3 mm), was used to shut out the sound waves that were outside of the mirrors, and to form the one centimetre square detection area. This multiple reflection sensor extends the external cavity length $L$ in a narrow space and thus, high sensitivity and spatial resolution were achieved.

### *3.2. Detection system*

The detection system of the conventional type laser microphone is shown in figure 2. The LD driver supplies constant DC current to the LD, and the photo current obtained from the photodiode is converted into signal voltage by an I-V converter, with the signal voltage being band limited and amplified. The pass band of Band-pass filter (BPF) was from 10 Hz to 200 kHz, and the voltage was amplified to 1500 overall. All the measurement circuits were placed in a steel case to shield them from external noise, and a mixed domain oscilloscope (Tektronix MDO-3022) was used for measurements. A Bose DS-16S full-range speaker was used as the planar sound source In an audible band (40 Hz–20 kHz), and a Pioneer PT-R4 super tweeter was used as a sound source in a supersonic band (20 kHz–170 kHz). The sound sources were set 20 cm apart from the centre of the sensors, at right angles.

The detection parts, their steel case, and the sound sources were placed in an anechoic box, for measurements, and in the case where the multiple reflection sensors were used, the sound detection parts in figure 2 were replaced with these sensor parts, while all other aspects of the configuration were the same as for the conventional laser microphone.

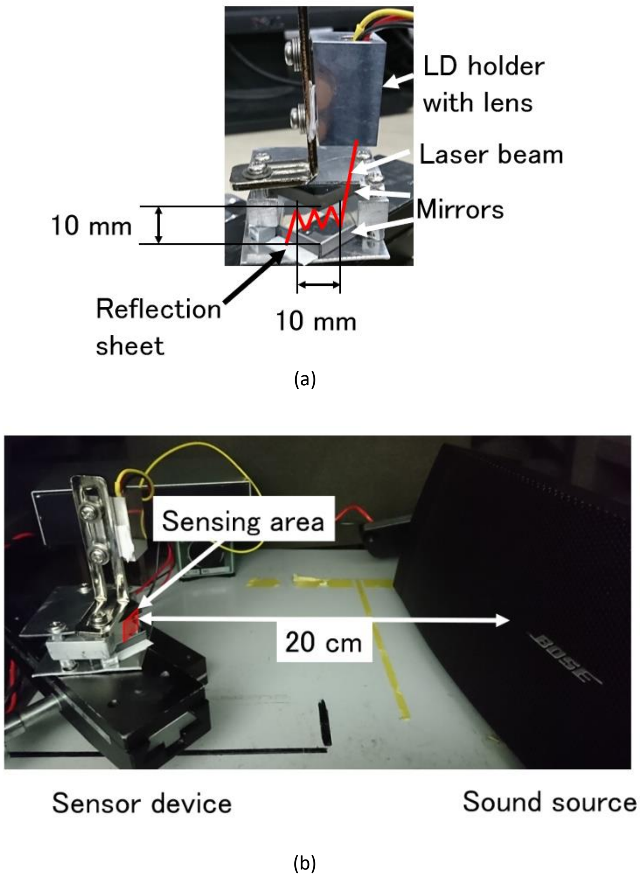



**Figure 1**. Schematic view of multiple reflection sensor parts: (a) sound wave incident plane view, (b) side plane view. (shown without insulator).

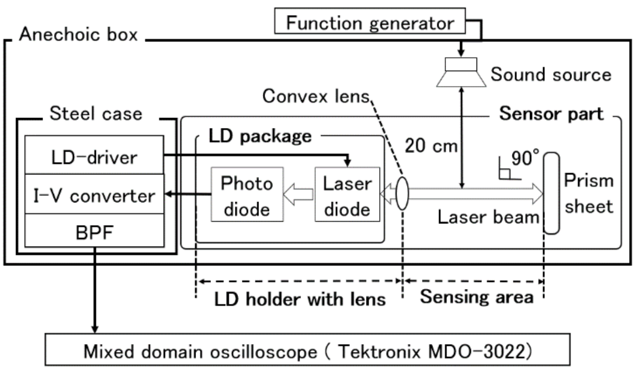



**Figure 2**. Detection system of a laser microphone.

## 4. Measurement results

### *4.1. Sound pressure characteristics and sensitivity*

With a laser power of 20 mW, and an Incident sound frequency of 1 kHz, the measured signal voltages for the sound pressure are shown in figure 3. The spectrum analyser function of a mixed domain oscilloscope was used for the measurements, and all the measurement values shown below are averages of five measurements. The dotted, dashed, solid, and dot-dash lines represent the approximated curves of the measurement values from the least square method. Changed folding multiples were performed by changing the laser beam incident angle, and the beam lengths which interact with the sound wave of 12 reflections, 8 reflections, and 4 reflections were approximately 10 cm, 6 cm, and 2 cm, respectively. The 'Conventional type' means the linear beam which was simply miniaturized to 1 cm.

From figure 3, the sensitivity of the laser microphone is the gradient with the characteristics of 2.7 mV/Pa, with the conventional type, or 18.3 mV/Pa with 12 reflections. Thus, the maximum sensitivity increased by approximately seven times, and the minimum detectable sound pressure decreased to 52 dB, by the multiple reflection sensor. From these results, it is apparent that we achieved high sensitivity and high spatial resolution simultaneously. Note that, due to the two percent reflective loss at each reflection, the sensitivities of the multiple reflection sensors decreased compared to the linear sensors at the same beam length.

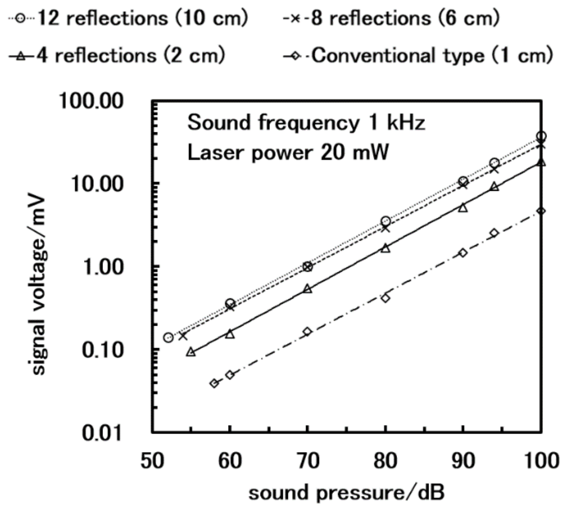



**Figure 3**. Signal voltage vs. sound pressure (planar wave).

### *4.2. Frequency characteristics*

With a laser power of 20 mW and a laser beam diameter of 1 mm, the incident sound frequency was changed from 40 Hz to 170 kHz, and the laser microphone signal voltage was measured at each frequency. In this section, the sensitivity of a laser microphone is defined by dividing the signal voltage by the incident sound pressure at each frequency. The frequency characteristics of laser microphones are shown in figure 4.

From figure 4, it can be seen that the frequency characteristics are almost flat with the 10 % error range. However, the sensitivities slightly decreased at 170 kHz. From previous research [11], the sensitivity decrease at higher frequencies is related to the ratio of sound wave wavelength and laser beam diameter. The sensitivity decrease at 170 kHz was due to the nature of the laser microphone mentioned above. Frequencies lower than 40 Hz were not measured, due to the absence of a suitable sound source, although, in principle, lower frequency characteristics become flat. From these results, it is apparent that the multiple reflection structure does not affect the frequency characteristics of a laser microphone.

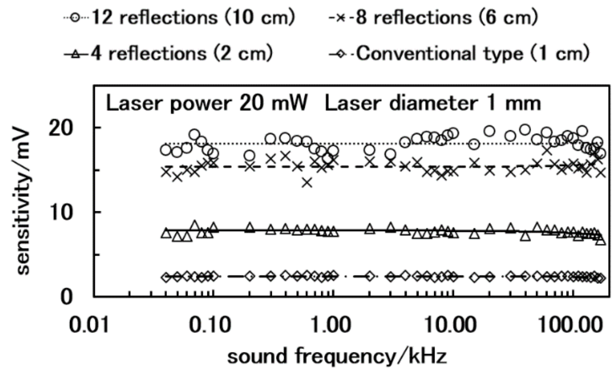



**Figure 4**. Frequency characteristics of a laser microphone (planar wave).

### *4.3. Spherical sound wave detection*

The sound source was changed to a Jazzman J-01X which generates spherical sound waves, and the measurement results for the multiple reflection sensors were then compared with those of a condenser microphone (BRÜEL & KJÆR Type 4939: detection area is 0.635 cm (one quarter inch) diameter). With a sound frequency of 10 kHz and a sound pressure of 1 Pa, the measured normalized sound pressure distributions are shown in figures 5 (a) and 5 (b). The distance from the sound source was five centimetres and the scanning area was five square centimetres.

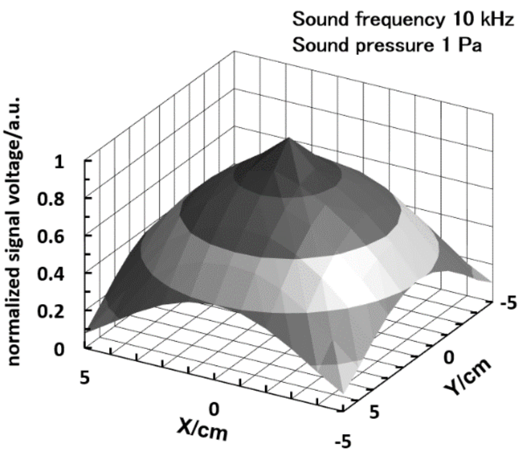
Figures 5 (a) and 5 (b) show respective results for a condenser microphone, and a laser microphone with a laser power of 20 mW and 12 reflections. The figures are similar, however, the high gradient parts at the centre of figure 5 (a) are absent from figure 5 (b), and this is because the detection area of the multiple reflection sensor is larger than that of the condenser microphone i.e., the spatial resolution of this sensor is less than the condenser microphone. For the rest of the conditions, the measurements for the two microphones were similar.

## 5. Conclusion

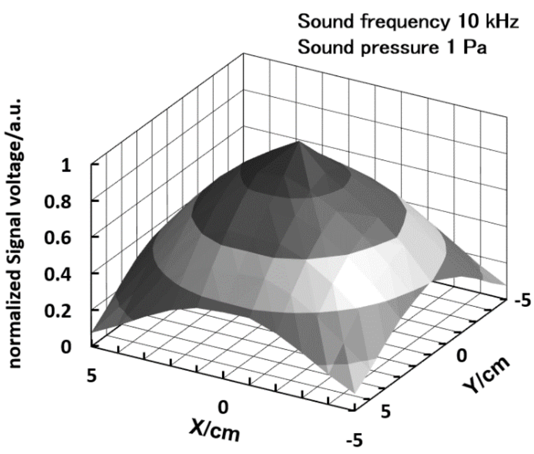
Detection of spherical sound waves is difficult for optical microphones, since the sensing area of the optical microphone requires a relatively large amount of space and so, in a conventional laser microphone, the sensor section must be several cm long. For this reason, if you simply miniaturise a conventional laser microphone to measure spherical waves, the sensitivity of the sensor will be reduced. To resolve this problem, we proposed a new sensor structure, using multiple reflections of a pair of mirrors. By using multiple reflections, it became possible to miniaturize the sensor section, and to measure spherical waves without lowering sensitivity.

Our testing results indicated that the sensitivity of the laser microphone was improved by up to approximately seven times, and the minimum detectable sound pressure was reduced by 5 dB, in comparison to simple miniaturization of the sensor part, when the multiple reflection sensor was used. We therefore achieved high sensitivity and high spatial resolution simultaneously. Furthermore, this multiple reflection structure did not affect the frequency characteristics of the test laser microphone which is an important outcome considering wide band applications.

In the case of spherical sound wave detection, the multiple reflection type laser microphone reconstructed the sound pressure distribution of 10 kHz the same as the commercial 0.635 cm (quarter inch) diameter condenser microphone.




(a)




(b)

**Figure 5**. Sound pressure distribution from a Jazzman J-01X (5 cm square area): (a) sound pressure distribution using a condenser microphone, (b) sound pressure distribution using a laser microphone.

Therefore, the multiple reflection type laser microphone resolved the difficulty of spherical sound wave detection. However, because the spatial resolution was inferior to that of the condenser microphone, higher gradient waves were not reproduced sufficiently by this sensor.

In the future, we will investigate ways to improve the spatial resolution and measurable conditions, and will also test this sensor's ability to work with small and near sound sources, or under special conditions.

## References

[1] G. Smeets 1977 *J. Acoust. Soc. Am.* **61** 872-75.
[2] M. H. de Paula, A. A. de Carvalho, C. A. Vinha, N. Cella, and H. Vargas 1988 *J. Appl. Phys.* **64** 3722-24.
[3] K. Ishikawa, K. Yatabe, N.Chitanont, Y. Ikeda, Y. Oikawa, T. Onuma, H. Niwa, and M. Yoshii 2016 *Opt. Express* **24** 12922-32.
[4] J. G. Choi and G. J. Diebold 1982 *Appl. Opt.* **21** 4087-91.
[5] K. Abe, K. Otsuka and J. Y. Ko 2003 *New J. Phys.* **5** 8.1-8.9.
[6] Y. Sonoda, Y. Nakazono 2012 *Adv. Acoust. Vib.* **2012** 1-17.
[7] B. Fischer 2016 *Nat. Photonics* **10** 356-8.
[8] S. Preisser, W. Rohringer, M. Liu, C. Kollmann, S. zotter, B. Fischer and W. Drexler 2016 *Biomed. Opt. Express* **7** 4171-86.
[9] T. M. Quist, R. H. Rediker, R. J. Keyes, W. E. Krag, B. Lax, A. L. McWhorter, and H. J. Zeigler 1962 *Appl. Phys. Lett.* **1** 91-2.
[10] A. L. McWhorter, H. J. Zeiger, and B. Lax 1963 *J. Appl. Phys.* **34** (1963) 235-6.
[11] D. Mizushima, T. Yamaguchi, T. Yoshimatsu, M. Aoki, N. Tsuda and J. Yamada 2018 *IEEJ. Trans. EIS* **138-E** 9-14.
[12] G. M. Norgia, S.Donati, and T.Bosch 2002 *J. Opt. A-Pure Appl. Opt.***4** S283-94.
[13] B. Edlén 1966 *Metrologia* **2** 71-80.
[14] P. E. Ciddor 1996 *Appl. Opt.* **35** 1566-73.
[15] T. Taimre, M. Nikolić, K. Bertling, Y. L. Lim, T. Bosch, and A. D. Rakić 2015 *Adv. Opt. Photon.* **7** 570-631.