Experimental investigation on a microphone using the change in the total reflection of light by sound

Yasushi Suzuki and Ken’iti Kido

Department of Electronic Media Technology, Gunma National College of Technology, 580 Toriba-cho, Maebashi, 371–8530 Japan
Professor Emeritus of Tohoku University, 543–1–504 Niiharu-cho, Midori-ku, Yokohama, 226–0017 Japan
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Abstract: A new microphone, which uses the optical total reflection at the boundary surface between glass and air, is investigated theoretically and experimentally. The critical angle for total reflection changes by the refractive index of air, which depends on the air density. The density changes by the sound pressure. Therefore, the sound pressure is measurable by detecting the intensity of the reflected light from the total reflection area, and it is expected that there is no limitation in the frequency range as the mechanical vibration is not used. The sound pressure sensitivity of the microphone and the effect of surrounding conditions are investigated theoretically. Some experiments are carried out to verify the theoretical investigations, employing a laser diode and a sensor made by cutting off a part of cylindrical glass rod. Experimental results show that the microphone can be used for the measurement of the waveform of high frequency sound though the sensitivity of the microphone is low as expected by the theoretical investigation. The remaining problem is to improve the sensitivity.

Keywords: Microphone, Optical total reflection, Refractive index, High sound pressure

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1. INTRODUCTION

Microphones with no diaphragm have big advantages. The mechanical structure is simple and the frequency range is not restricted as the mechanical vibration is not used to detect sound pressure. The optical measurement techniques make such microphones possible to be realized. The microphones using the optical techniques are expected to have excellent properties. In addition, they are not affected by the electromagnetic noise.

Some microphones without a diaphragm using optical techniques have been studied [1–4]. Those microphones, however, detect the averaged sound pressure in some spatial extent. We have proposed a method for measuring the sound pressure in a narrow space [5]. The method uses the optical total reflection on a boundary surface between glass and air. We have investigated theoretically the sensitivity of proposed microphone and shown that the microphone has feasibility for practical use if it has a curved boundary surface with very large radius of curvature [6–8].

The sensitivity of the microphone has been calculated so far assuming that all the rays incident to the boundary surface with the incident angle less than the critical angle for the total reflection penetrate through the surface. However, some part of the light expected to penetrate are reflected at the surface. In this paper, first, the sensitivity is calculated considering such reflected light and also the allowable range of the surrounding conditions are investigated. Next, we experimentally verify the proposed method for sound detection by detecting the sound pressure signal in a high sound pressure field [9–11]. It is shown that the microphone can have the possibility for practical use in high sound pressure and broad band measurements.

2. PRINCIPLES

The microphone uses the change in the amount of reflected light due to the sound, employing the plane-wave light beam incident on a curved boundary surface between glass and air. Figure 1 shows a quarter cross section of a cylindrical glass rod. Each ray of the incident beam with the width of $2r_0$ has a different angle of incidence. The upper rays of the beam have angles greater than the lower rays of the beam. If the ray incident on the critical point A...
has the total reflection angle $\theta_c$, the rays above A are totally reflected (totally reflected beam) and some of the rays below A also reflected (ordinary reflected beam), whereas most of them penetrate through the glass surface (transmitted beam). $R$ is the radius of the rod and $h$ is the distance from $x$-axis to the critical point A. Let $n_0$ be the refractive index of glass and $n_m$ be that of air, so that

$$\theta_c = \sin^{-1} \frac{n_m}{n_0} = \sin^{-1} \frac{h}{R}. \quad (1)$$

The sound pressure changes the refractive index of air. The critical angle moves by the fluctuation in the refractive index and consequently the position of A changes, which results in the change in the intensity of reflected light. Therefore, the sound pressure can be detected by measuring the quantity of reflected light.

### 2.1. Sensitivity of the Microphone

The reflectances for $p$- and $s$-polarized light are given as follows [12]:

$$\alpha_p = \left( \frac{n^2 \cos \theta_i - \sqrt{n^2 - \sin^2 \theta_i}}{n^2 \cos \theta_i + \sqrt{n^2 - \sin^2 \theta_i}} \right)^2, \quad (2)$$

$$\alpha_s = \left( \frac{\cos \theta_i - \sqrt{n^2 - \sin^2 \theta_i}}{\cos \theta_i + \sqrt{n^2 - \sin^2 \theta_i}} \right)^2,$$

where $\theta_i$ is the angle of incidence and $n = n_m/n_0$. If $\theta_i \geq \theta_c$, the reflectances are not expressed by Eqs. (2) and they are given as $\alpha_p = \alpha_s = 1$.

For simplifying the calculation, we use the approximate expression of Eqs. (2). If $\delta h$ is the distance from $h$ in the direction to $y$-axis in Fig. 1, Eqs. (2) are approximated as follows. The relation between $\theta_i$ and the incident position $\delta h$ is given by the following equations.

$$\sin \theta_i = n + \frac{\delta h}{R}, \quad \cos \theta_i = \sqrt{1 - \left( n + \frac{\delta h}{R} \right)^2}. \quad (3)$$

where $\delta h \leq 0$ because $\alpha_p = \alpha_s = 1$ in the case that $\delta h > 0$. By substituting Eqs. (3) into Eqs. (2) and using $|\delta h/R| << 1$, Eqs. (2) are calculated to the first-order approximations to be

$$\alpha_p = \left\{ \begin{array}{ll}
\frac{n^2 a - b \sqrt{-\frac{\delta h}{R}} + n^2 c \left( -\frac{\delta h}{R} \right) - d \left( -\frac{\delta h}{R} \right)^2}{n^2 a + b \sqrt{-\frac{\delta h}{R}} + n^2 c \left( -\frac{\delta h}{R} \right) + d \left( -\frac{\delta h}{R} \right)^2} \end{array} \right\}, \quad (4)$$

$$\alpha_s = \left\{ \begin{array}{ll}
\frac{a - b \sqrt{-\frac{\delta h}{R}} + c \left( -\frac{\delta h}{R} \right) - d \left( -\frac{\delta h}{R} \right)^2}{a + b \sqrt{-\frac{\delta h}{R}} + c \left( -\frac{\delta h}{R} \right) + d \left( -\frac{\delta h}{R} \right)^2} \end{array} \right\},$$

where

$$a = \sqrt{1 - n^2}, \quad b = \sqrt{2n}, \quad c = \frac{n}{\sqrt{1 - n^2}}, \quad d = \frac{1}{2\sqrt{2n}}.$$

Furthermore, by approximating Eqs. (4), using $\sqrt{-\delta h/R} \ll 1$, the reflectances are reduced to the following expressions.

$$\alpha_p \approx 1 - \frac{4\sqrt{2}}{n^2} \frac{\sqrt{n}}{1 - n^2} \sqrt{\frac{n}{R}}, \quad (5)$$

$$\alpha_s \approx 1 - \frac{4\sqrt{2}}{n^2} \frac{\sqrt{n}}{1 - n^2} \sqrt{\frac{n}{R}}$$

A sketch of the reflectances in Eqs. (2) and Eqs. (5) versus $\delta h$ is shown in Fig. 2, using the following practical values.

$$n_0 = 1.51633 \text{(for BK7)},$$

$$n_m = 1.0002713 \text{(for a red light at } 633 \text{ nm)},$$

$$R = 11 \text{ m}.$$

In order to calculate the sensitivity, we use the reflectances in Eqs. (5) and suppose that the incident beam shapes a rectangle and has a width of $2r_0$ as shown in
[Fig. 3] Approximated reflectance curve.

Fig. 3 illustrates that the change in the intensity of reflected light by the sound pressure. \( r \) is the distance from \( h \). When there is no sound, the reflectance for the incident beam light is expressed by the solid line as the function of incident position. The critical point expressing the boundary line of the total reflection region is at \( h \). If the atmospheric pressure increases by sound, the critical point moves \( \delta h \) to the right as shown in the figure. Consequently, the intensity of the reflected light decreases. When the critical point is at \( h + \delta h \) as shown in the figure, the intensity of \( p \)-polarized reflected light is computed as follows.

\[
S_p(\delta h) = W - \left[ - \int_{-r_0}^{0} \{ \alpha_p(r) - 1 \} dr \right] \\
= 2r_0 - \frac{8\sqrt{2}n}{3n^2\sqrt{1 - n^2}} \left( r_0 + \delta h \right)^{\frac{3}{2}}
\] (7)

Where, \( W = 2r_0 \times 1 \): the total amount of the incident light and \( 2r_0 \): the width of the light beam.

When the reflectance is given by the solid line, the intensity is

\[
S_p(0) = 2r_0 - \frac{8\sqrt{2}n}{3n^2\sqrt{1 - n^2}} r_0^3 \sqrt{\frac{n}{R}}
\] (8)

If the critical point moves \( \delta h \) by the sound, the change in the intensity of reflected light \( \delta S_p \) is expressed by

\[
\delta S_p = S_p(\delta h) - S_p(0)
\]

\[
= - \frac{8\sqrt{2}n}{3n^2\sqrt{1 - n^2}} r_0^3 \sqrt{\frac{n}{R}} \left\{ \left( 1 + \frac{\delta h}{r_0} \right)^{\frac{3}{2}} - 1 \right\}
\] (9)

By using \( |\delta h/r_0| \ll 1 \), Eq. (9) is approximated as follows.

\[
\delta S_p \equiv - \frac{4\sqrt{2}n}{n^2\sqrt{1 - n^2}} \sqrt{r_0^3} \cdot \sqrt{\frac{n}{R}} \cdot \delta h
\] (10)

The ratio of \( \delta S_p \) to \( W \) is that

\[
D_p = \frac{\delta S_p}{W} = - \frac{4\sqrt{2}}{2r_0^2n^2} \sqrt{\frac{n}{1 - n^2}} \sqrt{\frac{r_0}{R}} \cdot \delta h
\]

\[
= - \frac{2\sqrt{2}}{n^2} \sqrt{\frac{n}{1 - n^2}} \frac{\delta h}{\sqrt{r_0R}}
\] (11)

The relation between sound pressure \( \delta p \) and movement of the critical point \( \delta h \) is calculated as follows [13]:

\[
\delta h = \frac{n_m - 1}{n_0\gamma P_0} R \cdot \delta p,
\] (12)

where, \( P_0 \) is the atmospheric pressure and \( \gamma \) is the ratio of specific heat.

By substituting Eq. (12) and \( \delta p = 1 \text{ Pa} \) into Eq. (11), the sensitivity of the microphone for \( p \)-polarized light is given by the following equation.

\[
\sigma_p = D_p |_{\delta p=1} = - \frac{2\sqrt{2}}{n^2} \sqrt{\frac{n}{1 - n^2}} \frac{n_m - 1}{n_0\gamma P_0} \sqrt{\frac{R}{r_0}} \text{ [Pa]}
\] (13)

The sensitivity of the microphone for \( s \)-polarized light is given by the following equation by using a similar procedure.

\[
\sigma_s = - \frac{2\sqrt{2}}{n^2} \sqrt{\frac{n}{1 - n^2}} \frac{n_m - 1}{n_0\gamma P_0} \sqrt{\frac{R}{r_0}} \text{ [Pa]}
\] (14)

The sensitivity of the microphone is proportional to \( \sqrt{R/r_0} \). If we make \( R \) larger, the sensitivity will be higher. The difference between \( \sigma_p \) and \( \sigma_s \) is only a term \( 1/n^2 \).

Figure 4 shows the sensitivities \( \sigma_p \) and \( \sigma_s \) as the function of the ratio of the radius of curvature \( R \) to the width of the light beam \( r_0 \) which are computed using the values in Eq. (6) and \( \gamma = 1.403, P_0 = 1.013 \text{ hPa} \).
The sensitivity of the microphone employed $p$-polarized light is $1/n^2 (= 2.30)$ times larger than that employed $s$-polarized light in this case.

### 2.2. Effects of the Fluctuation of Surrounding Conditions

The refractive index of air changes by the fluctuation of the surrounding conditions such as atmospheric pressure and temperature. The refractive index of air for the red light of He-Ne laser around the industrial normal state (temperature: 20°C, atmospheric pressure: 1,013 hPa, vapor pressure: 13.33 hPa, concentration of CO$_2$: 0.03%) is approximately given by the following equation [14].

\[
(n_m - 1) \times 10^6 = 271.30 - 0.93(t - 20) + 0.27(P - 1013) - 0.0375(P_w - 13.33) + 0.02(k - 3) \tag{15}
\]

where $t$ is a temperature in °C, $P$ and $P_w$ are the atmospheric pressure and the vapor pressure in hPa respectively, and $k$ is the concentration of the carbon dioxide in 0.01% unit.

The atmospheric pressure and the temperature affect the refractive index of air much more largely than the other conditions do. The biggest problem caused by the fluctuation of surrounding conditions is that the critical point can move outside the incident beam. The microphone will lose the sensitivity in such the case. It is significant when the radius of curvature of the curved surface is made very large to improve the sensitivity.

The position of the total reflection $h$ is expressed by Eq. (1). Let $\Delta n_m$ be the fluctuation of the refractive index of air, then the permissible range $\Delta h$ is given by the following equation.

\[
\Delta h = \frac{\Delta n_m}{n_0} R \leq |r_0| \tag{16}
\]

Therefore, the allowable range of the atmospheric pressure $P_{\text{max}}$ [hPa] can be computed as the function of temperature and $r_0/R$.

\[
\left\{ 3.44(t - 20) - 5.62 \left( \frac{r_0}{R} \times 10^6 \right) \right\} + 1013 \leq P \\
\leq \left\{ 3.44(t - 20) + 5.62 \left( \frac{r_0}{R} \times 10^6 \right) \right\} + 1013 \tag{17}
\]

The allowable range of the atmospheric pressure computed by Eq. (17) is plotted in Fig. 5. The area shut in by a pair of lines is the range for the microphone to have the sensitivity. If $R/r_0$ is increased to get higher sensitivity, the range becomes narrower. Therefore, it is needed for practical use that the invention to adjust the sensing part automatically and conform the incident angle of the beam to the critical angle, according to the movement of the position of the total reflection due to the fluctuation of the surrounding condition.

### 3. EXPERIMENTS

#### 3.1. Sensor

Figure 6 shows the sensor employed in the experiments. The sensor is a part cut off from a cylindrical glass rod shown in Fig. 1. The dotted line A indicates the border of the total reflection area. The radius of curvature $R$ is 11 m. The sensor is glued to the brass plates as shown in the picture to fix on the experimental apparatus. If the incident beam with a width of 1.0 mm is employed, the sound pressure sensitivities $\sigma_p$ and $\sigma_t$ are supposed to have the following values, according to Eq. (13) and Eq. (14). The values in Eq. (6) and $\gamma = 1.403$, $P_0 = 1013$ hPa are used for the calculation.

\[
\sigma_p = -1.32 \times 10^{-6} \text{ [Pa]}, \\
\sigma_t = -0.571 \times 10^{-6} \text{ [Pa]} \tag{18}
\]

According to Fig. 5, the effect of the surrounding conditions may be neglected in this case because $R/r_0 = 2.2 \times 10^4$.

#### 3.2. Experimental Methods and Results

3.2.1. Detection of sinusoidal sound pressure signal using polarized light

The experimental arrangement is shown in Fig. 7. The laser light emitted from a laser diode (635 nm, 4.9 mW) is...
incident on the surface, involving the border of total reflection. The laser beam has a diameter of about 1.0 mm. The laser light is polarized by a polarizing beam splitter.

The reflected beam is received by a photodiode passing through a polarizing beam splitter again, and the output of the diode is analyzed by the FFT analyzer. The waveform of the output signal is observed by the oscilloscope, using the low pass filter (70 kHz) and the amplifier (+6 dB) to improve the S/N. A ultrasonic transducer (S.P.L: 115 dB/(10 Vpp) at 30 cm, f₀: 40 kHz) is used as the sound source and is placed very close to the sensor to get a high sound pressure. The incident position of signal light is adjusted to the optimum position by using the X-axis stage and the rotating stage, monitoring the FFT analyzer.

Figures 8 and 9 show the power spectra and the waveform of the output signal. The input voltage to the transducer is 10 Vpp and the driving frequency is 40 kHz. The sound pressure level at the sensing surface is considered to be about 140 dB, since the transducer is set about 1.5 cm apart from the surface. The reflected light produces 12.5 V at the output terminal of the photodiode, which represents the total amount of the incident light W. The output voltage level by the sound signal is, therefore, estimated to be about −50 dBV if the light is completely p-polarized and about −57 dBV if completely s-polarized.

The reflected light has a spectrum with the magnitude of about −44 dBV at 40 kHz in Fig. 8(a) and about −52 dBV at 40 kHz in Fig. 9(a). The results indicate that the sound pressure is detected by this system. Although the S/N is low, the sinusoidal wave of 40 kHz can be observed in both Fig. 8(b) and Fig. 9(b). The measured peak values of the spectrum are larger than the calculated values. It is considered that the sound pressure increases at the sensing point by the influence of the reflected sound.

The relation between the peak spectrum and the distance between the sensor and the sound source is shown in Fig. 10, which shows that the sound pressure is affected by the reflected sound, but it is almost inversely proportional to the separation between the sensor and the sound source on average. The fluctuation of the peak spectrum as the distance can be caused by the reflection of sound between
the sound source and the sensor because the intervals of the fluctuation are about a half of the wavelength.

Figure 11 shows the waveforms of the output signal when employing the ultrasonic transducers with oscillating frequencies of 110 kHz and 200 kHz to demonstrate that the frequency range of the microphone is extremely broad. Although the S/N is low, it is shown that the microphone can detect much higher frequency sound than the conventional microphones as predicted in principle. The precise experiments will be carried out in the next stage.

3.2.2. Effect of vibration of the system

Figure 12 shows the experimental arrangement around the sensor for examining the effect of vibration of the system. The laser light emitted from L.D. is split into two beams by a non-polarizing beam splitter. One is incident on a region involving the border with the total reflection area as the signal light. The other is incident on the total reflection area as the reference light for monitoring the vibration of the system. Besides the ultrasonic transducer, a tweeter (S.P.L.: 100 dB/W(m), 4–40 kHz) is used for the sound source and is placed about 3 cm apart from the sensor to get a high sound pressure. The input to the tweeter is 1 W, so the sound pressure level at the sensing surface is considered to be about 130 dB in this case. Each beam is received by a photodiode, and the outputs are analyzed by the FFT analyzer.

Figure 13 shows the power spectra of the signal light and the reference light in the cases that the driving frequencies of the sound sources are 40 kHz, 14.5 kHz and 12 kHz, respectively.
Each signal light has a peak spectrum at the driving frequency in the spectra, which indicates that the microphone detects the sound pressure. The reference light in Fig. 13(c) has a peak at the driving frequency in the spectra, whereas that in Fig. 13(a) or (b) has no peaks in its spectra. Therefore, in this case of arrangement the microphone can be affected by the vibration of the system up to the driving frequency of about 12 kHz. However, it is considered that the effect of vibration can be removed by fixing the L.D. and P.D. to the sensor.

3.2.3. Detection of an impulsive high pressure sound using \( p \)-polarized light

Figure 14 shows the experimental arrangement around the sensor. \textit{Hyoshigi} is used as a impulsive sound source and is clapped about 7 cm away from the sensor. The sound level meter (NA-20, RION, 40–130 dB, 10–20,000 Hz) adjusted to have flat frequency response is placed about 60 cm apart from the sound source, monitoring the sound pressure. The output of the P.D. is observed by the oscilloscope passing through the L.P.F (70 kHz) and the amplifier (+6 dB) with the output of the sound level meter.

The observed waveforms of the outputs are shown in Fig. 15. Although the S/N is low, and the waveforms are not the same because of the reflecting objects around the sensor and the difference in the distance from the source to the sensor and the sound level meter, the experiment shows that the microphone detects the impulsive sound. Figure 15 indicates that the microphone can detect much higher frequency components than the sound level meter. The time lag of about 1.5 ms exists between the waveforms, which is caused by the separation of about 53 cm between the sensor and the sound level meter.

The waveform (a) predicts the maximum sound pressure of about 149 dB at the sensing surface because its peak value is about 130 dB. From the waveform (b), however, the peak of the sound pressure at the sensing surface is estimated to be about 164 dB, using Eq. (18) and the measured values that are 100 mV (the peak value of the waveform) and 12.5 V (the output voltage of the P.D.).

4. CONCLUSION

This paper describes a microphone which uses the
optical total reflection on a curved boundary surface between glass and air. The sound pressure sensitivity of the microphone and the range of the surrounding conditions for the microphone to have the sensitivity are calculated.

Some experiments are carried out to verify that the sound pressure can be detected by the proposed method. A sensor made by cutting off a part of a cylindrical glass rod is employed and the polarized light emitted from a laser diode is used as the light source. As the sensitivity of the sensor employed is low, the experimental results can not be obtained, except in a high sound pressure field. Therefore, the sensor should be placed very close to the source so that the sound pressure is more than 130 dB in the experiment.

In the results of the sinusoidal sound detection experiment, the spectra of the reflected light contain the outstanding peak at the driving frequency of the sound source with the magnitude nearly expected. The waveform of the sound is also observed, though the S/N is low. Therefore, it is confirmed that the sound pressure can be measured by the proposed microphone and the frequency range of the microphone is extremely broad.

The experimental results for the effect of vibration on the system show that the mechanical vibration can affect the system up to about 12 kHz in this case of the arrangement. However, making the sensor unified with the light source and the detector, the effect of the vibration may be decreased to the negligible level.

The microphone can detect the impulsive high sound pressure which has the maximum value of more than 160 dB. Therefore, it has feasibility for practical use in high sound pressure and broad band measurements.

In order to detect the waveform of ordinary pressure sound, we are going to improve the sensitivity. The sensitivity can be improved by making the radius of curvature \( R \) large, but the sensor with very large \( R \) is extremely sensitive to the fluctuation of surrounding conditions. The solution to the problem by controlling the direction of incident beam is now under investigation. The result will be reported in the next stage.

REFERENCES


Yasushi Suzuki received his B.E. and M.E. degrees from Gunma University in 1977 and 1979, respectively. He is currently an associate professor at Gunma National College of Technology. His research interests include electro-acoustics and acoustic measurement. He is a member of the Acoustical Society of Japan and the Institute of Electronics, Information and Communication Engineers.

Ken'iti Kido was born in 1926 and he received his B.E. and Dr. Eng. degree from Tohoku University, Japan in 1948 and 1962, respectively. From 1963 to 1976, he was Professor at the Research Institute of Electrical Communication, Tohoku University, where he was a chief of the Division of Acoustics and Communication. He was also Professor at the Faculty of Engineering where he had some lectures. From 1976 to 1990, he was Director and Professor at the Research Center for Applied Information Science, Tohoku University. The research area of this center covered the Engineering, Economics and Biology as the main branches of the Information Science. In 1990, he retired from Tohoku University and was conferred the title of Professor Emeritus. From 1990 to 2002 he was professor at the Chiba Institute of Technology. He was President of the Acoustical Society of Japan from 1983 to 1985. He established the Western Pacific Acoustical Conference in 1982 which is held every 3 years and he is now Founder Chairman of the Western Pacific Commission for Acoustics. Since 1948, he has engaged in the researches on the acoustics and information science, mainly in the electro acoustics, noise control, architectural acoustics, psycho-acoustics, speech recognition and synthesis, linguistics, active control of sound and digital signal processing. He is an Emeritus of the Acoustical Society of Japan, a fellow of the Acoustical Society of America, a fellow of the Institute of Electronics, Information and Communication Engineers, a life member of IEEE and member of some other academic societies.