Improvement of the signal-to-noise ratio in a glass-based guided-wave optical microphone

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ABSTRACT

In this study, the signal-to-noise ratio of a glass-based guided-wave optical microphone was successfully improved by both increasing sensitivity and reducing noise. The optical microphone has a square diaphragm as a pressure-sensitive structure and a straight single-mode waveguide across the diaphragm. Sensitivity of the microphone and resonance frequency of the diaphragm are dependent on the area and thickness of the diaphragm. In this study, in order to increase sensitivity, the diaphragm dimensions were enlarged from 16 mm×16 mm×0.15 mm in the previous study to 20 mm×20 mm×0.15 mm. According to theoretical calculations, the phase sensitivity and resonance frequency were 2.5 mrad/Pa and 3.4 kHz for a 20 mm×20 mm×0.15 mm diaphragm, respectively. The sensitivity was theoretically expected to be twice as high as that in the previous study. To reduce noise, a bandpass filter with passband from 300 Hz to 3 kHz was employed. After fabrication of the optical microphone, sound pressure, ranging from 100 to 122 dB-SPL, was applied to the microphone with a frequency of 1 kHz. The measured output of the optical microphone was almost proportional to the sound pressure, and the minimum detectable sound pressure level of the microphone was experimentally evaluated to be 100 dB-SPL.

Keywords: optical microphone, guided-wave optics, glass, diaphragm, elasto-optic effect

1. INTRODUCTION

In clinical Magnetic Resonance Imaging (MRI) and functional MRI (fMRI), microphones are useful tools for communication between patient and physician. Dynamic microphones based on the electromagnetic effect cannot be, however, used under the strong magnetic fields occurring during MRI operation. Also, condenser microphones are unavailable in the MRI scanner room since the metal parts of the microphones degrade the MR image. On the other hand, microphones using lightwave sensing technology are available even in high magnetic fields like the MRI, because the microphones are not susceptible to electromagnetic interference and require no metal parts. A number of optical microphones have been developed to detect sound waves even under strong electromagnetic fields.[1-4] Our group has also demonstrated silicon-based and glass-based guided-wave optical microphones.[3,4] The guided-wave optical microphones have advantages such as alignment-free and stout configurations, compactness and lightness besides immunity to electromagnetic interference. In our previous study, the minimum detectable sound pressure level of a fabricated glass-based guided-wave optical microphone was estimated to be 140 dB-SPL or higher.[3] Since it is desirable that the optical microphone detect normal speech ranging from 55 to 65 dB-SPL, the signal-to-noise ratio (S/N ratio) of the guided-wave optical microphone must be improved by a factor of more than 10^4 by increasing sensitivity and reducing noise. Incidentally, sensitivity of the microphone and resonance frequency of the diaphragm are dependent on the diaphragm dimensions. In this study, in order to increase sensitivity, the diaphragm area was changed from 16 mm×16 mm in the previous study to 20 mm×20 mm. The diaphragm thickness remained 0.15 mm, the same as previously reported. Phase sensitivity of the fabricated microphone was experimentally evaluated to be 2.4 mrad/Pa, which is 2.6 times higher than that in the previous report.[3] Also, noise of the optical microphone was drastically reduced by a bandpass filter with passband from 300 Hz to 3 kHz. By increasing sensitivity and reducing noise, the S/N ratio was

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improved by a factor of approximately 100. The fabricated optical microphone successfully responded to the applied sound, and its minimum detectable sound pressure level was evaluated to be 100 dB-SPL.

2. PRINCIPLE OF OPERATION

Figure 1 shows the proposed glass-based guided-wave optical microphone. The microphone has a square diaphragm as a pressure-sensitive mechanical structure and a single-mode optical waveguide on the diaphragm. A shielding plate with a small hole is attached to the microphone to shield the bottom face of the diaphragm from diffracted sound waves, so that only the top face of the diaphragm is exposed to sound pressure. A small hole is provided to avoid any influence caused by fluctuations in atmospheric pressure. Moreover, in order to separate electronic devices, such as the light source and the photodetector, from the microphone head, a polarization-maintaining fiber is connected to one endface of the microphone, and a mirror is attached to the other end. A lightwave from a laser is sent to the optical microphone by the fiber. Then, a lightwave modulated on the diaphragm reflects back to the fiber by the end mirror.

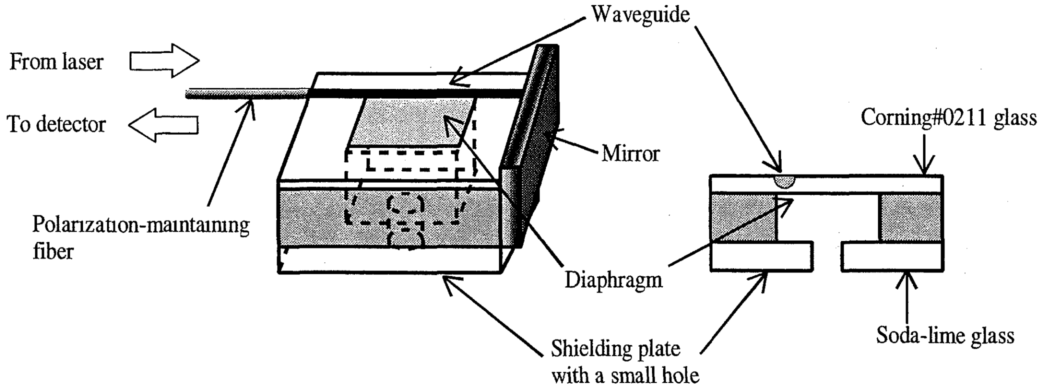


Fig 1 Schematic drawing of a glass-based guided-wave optical microphone.

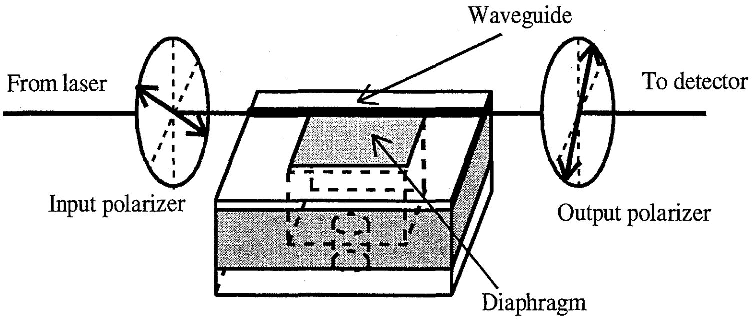


Fig. 2 Schematic diagram of a guided-wave optical microphone placed between a pair of crossed polarizers.

Such a sophisticated configuration is for practical applications. However, a simpler structure would be appropriate in the first phase of the study. Figure 2 illustrates a schematic diagram demonstrating the operation principle of a guided-wave optical microphone. An optical microphone is placed between a pair of crossed polarizers, as shown in Fig. 2. The input polarizer is oriented at 45° with respect to the polarization of each guided mode. The light beam from the input polarizer is coupled to the fundamental TM-like and TE-like modes at equal intensities. When a sound wave is applied to the diaphragm, the diaphragm is slightly distorted. The distortion causes strain, which produces a change in the refractive index of the waveguide on the diaphragm by the elasto-optic effect. The index change yields phase retardation in the lightwave, which propagates in the waveguide. Phase retardation is dependent on the guided modes, and phase difference between the two modes is also a function of the applied pressure. The lightwave has linear, elliptic or circular polarization at the end of the waveguide corresponding to the induced phase difference. The crossed output polarizer converts the polarization-modulated light into intensity-modulated light. The power of the beam passing through the output polarizer changes with the magnitude of sound pressure.

3. DESIGN AND FABRICATION

3.1 Designing of the guided-wave optical microphone

Sensitivity and resonance frequency are important factors in determining microphone performance, and are known to be dependent on the dimensions of the diaphragm.[3,4,6,7] In this study, phase sensitivity, defined as the induced phase difference per unit pressure, is used as microphone sensitivity. The phase sensitivity and the resonance frequency were calculated, following the mathematical description in Refs. 3 and 5, and the data was used to make the chart shown in Fig. 3 to design the guided-wave optical microphone. In the calculation, it was assumed that the diaphragm was square in shape and all edges of the diaphragm were rigidly clamped. Also, the diaphragm edge was chosen as the waveguide position, where sensitivity is the highest. The wavelength of the guided light was also set at 633 nm. Moreover, we used the mechanical and optical parameters of Corning #0211 glass, the material of the diaphragm, except for the elasto-optic coefficients, where the parameters of fused silica were used. The coefficients of fused silica are similar to those of the glass, so the use of the elasto-optic coefficients of fused silica does not result in a serious error to the theoretical results. In Fig. 3, the calculated trajectories of equal sensitivities are shown with solid lines on the side length - thickness plane. Since the phase sensitivity is proportional to the cube of the side length, and also inversely proportional to the square of the diaphragm thickness, the slopes for the sensitivities are 1.5 in Fig. 3. Moreover, the calculated trajectories of equal resonance frequency are shown with dashed lines in Fig. 3. Since the resonance frequency is proportional to the thickness of the diaphragm, and is also inversely proportional to the square of the side length, the slopes for the resonance frequencies are 2 in Fig. 3.

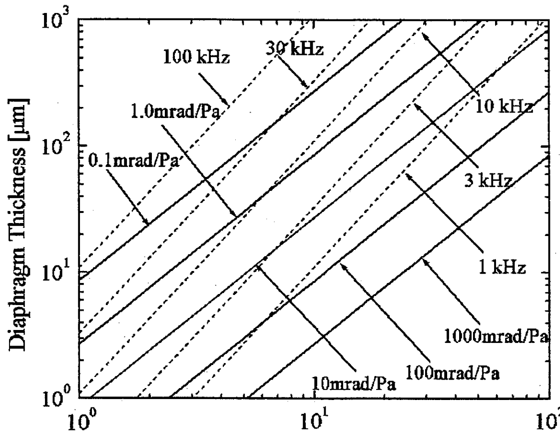


Fig. 3 Theoretical trajectories of equal sensitivities and equal resonance frequencies on the side length - thickness plane.

From Fig. 3, with an increase in side length of the diaphragm, sensitivity is found to increase, while resonance frequency decreases. Also, with a decrease in thickness of the diaphragm, sensitivity increases, while resonance frequency decreases. Since it is difficult to achieve both higher sensitivity and higher resonance frequency, one of these conditions may need to be sacrificed in order to satisfy the other when designing the guided-wave optical microphone.

The main concern of this study was placed on sensitivity rather than resonance frequency from the viewpoint of the improvement of the S/N ratio. The target value of sensitivity was set higher than 2.5 mrad/Pa, which is twice as high as the theoretical sensitivity of the previous report.[3] Also, in order to detect normal speech, the resonance frequency is required to be set higher than 3 kHz. From Fig. 3, the diaphragm dimensions were determined to be 20 mm × 20 mm × 0.15 mm. According to the theoretical calculations, phase sensitivity and resonance frequency were 2.5 mrad/Pa and 3.4 kHz, respectively.

3.2. Fabrication of the guided-wave optical microphone

Figure 4 shows a schematic drawing of the fabricated optical microphone with actual dimensions. The microphone was built using two glasses: a Corning #0211 glass as a diaphragm plate and a soda-lime glass with a 20 mm×20 mm square hole to support the diaphragm plate. First, a thin aluminum film was evaporated on a Corning glass with a thickness of 0.15 mm. On the aluminum film, the waveguide pattern was engraved by photolithographic process. Then, the glass was immersed in KNO_3 for two hours at 400 °C to form the single-mode channel waveguides. The waveguide was adjusted to be parallel to the diaphragm edge, and then the two substrates were bonded by UV adhesion. Finally, a shielding plate with a small hole was attached to the microphone to protect the bottom of the diaphragm from diffracted sounds.

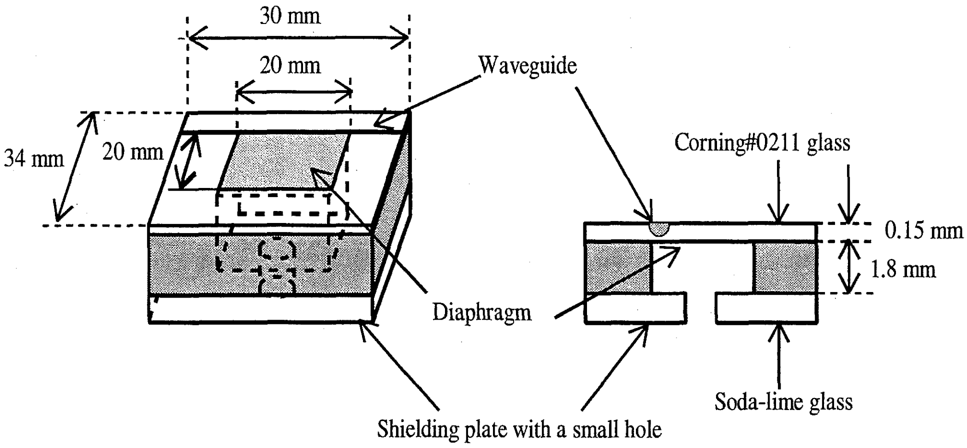


Fig. 4 Schematic diagram of the fabricated optical microphone with actual dimensions.

4. MEASUREMENTS

4.1. Output power in response to static pressure

Output power in response to static pressure was measured to evaluate phase sensitivity of the fabricated optical microphone. Figure 5 illustrates the experimental setup. In the measurements, a linearly-polarized He-Ne laser at 633 nm was employed as the light source. The polarization of the laser beam was set at 45° with respect to the microphone surface, so the input polarizer as shown in Fig. 2 was not necessary. Pressure was applied to the diaphragm by connecting a 3 ml syringe to the microphone with a silicone tube. Pulling and pushing the plunger of the syringe caused pressure difference, ranging from –3.0 kPa to 3.1 kPa, on the diaphragm. A positive value represents that pressure in the closed space under the diaphragm is higher than that in the atmosphere. Moreover, output light from the microphone was passed through a pinhole to block stray light. Output power was detected by a conventional photodetector.

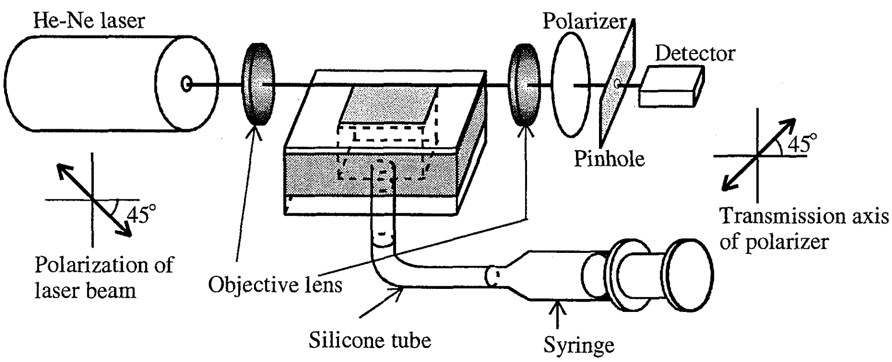


Fig. 5 Experimental setup used to evaluate phase sensitivity.

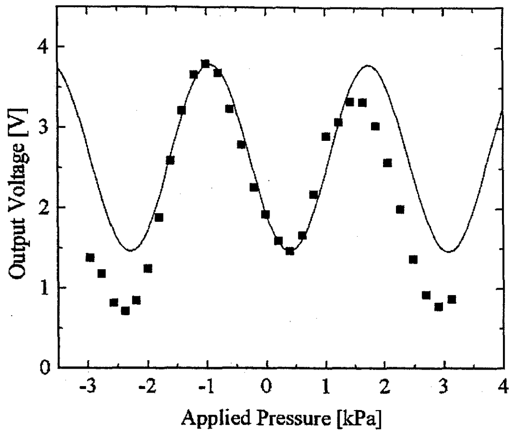


Fig. 6 Output voltage of the photodetector versus applied pressure.

Figure 6 shows the measured output voltage of the photodetector as a function of applied pressure. Filled squares in the figure represent the experimental data, and the solid line indicates the computer projection of the experimental data. Output power sinusoidally changes with applied pressure. A half period of the output power is called the halfwave pressure, which corresponds to a phase difference of π rad. From Fig. 6, the halfwave pressure was evaluated to be 1.3 kPa, corresponding to a phase sensitivity of 2.4 mrad/Pa. The measured sensitivity was almost same as the theoretical one, and was 2.6 times higher than that in the previous report.

4.2. Microphone signal in response to sound wave

Figure 7 shows the experimental setup to measure output power in response to a sound wave. A loudspeaker with a diameter of 80 mm was used as the sound source. To decrease mechanical vibration of the optical system due to the loudspeaker, the loudspeaker was physically isolated from the optical table by hanging it above the fabricated optical microphone with wires. Sound pressure, ranging from 2 Pa to 25 Pa, with a frequency of 1 kHz, was applied to the microphone. Sound pressure was calibrated using an electret condenser microphone with a known sensitivity. In the experiment, a bandpass filter with passband from 300 Hz to 3 kHz was utilized to reduce noise. The output of the bandpass filter was stored in the computer, after A/D converted.

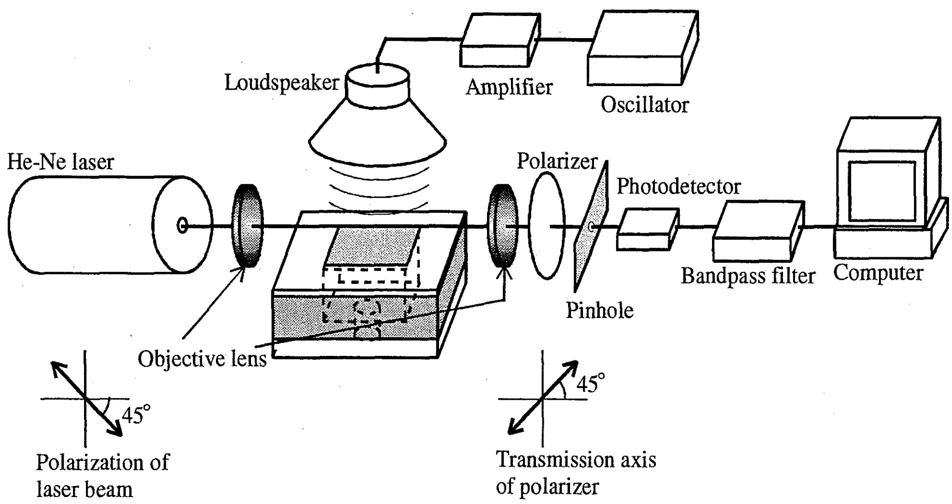


Fig. 7 Experimental setup to measure the output power as a function of the applied sound pressure.

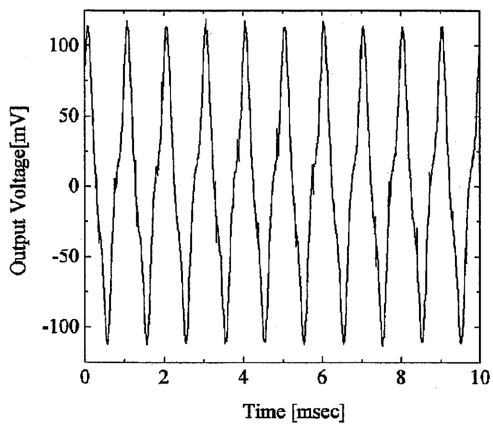
Figure 8(a) shows the output signal in response to a sound wave of 25 Pa and 1 kHz. An intensity-modulated output with the same frequency as the applied sound wave was observed, and the effective value of the output signal was 65 mV. Incidentally, from Fig. 6, the tangential slope was determined to be 1.9 V/kPa at 0 kPa, which is the operating point of the microphone. From the tangential slope of 1.9 V/kPa, the output signal is estimated to be 48 mV for a sound pressure of 25Pa. The estimated output signal was less than the measured one. The output signal of the optical microphone may be partially caused by the misalignment of the optical components, including the fabricated microphone, due to mechanical vibration. So, the output signal obtained in the experimental setup as shown in Fig. 7 is called the nominal microphone signal in this paper.

In order to confirm whether the observed output signal, that is, the nominal microphone signal was produced by the elasto-optic effect, the output power was measured with the output polarizer removed from the experimental setup. No intensity-modulated output should occur if the output light is affected only by the elasto-optic effect. Undesired intensity-modulated output without the polarizer suggests an induced misalignment of the optical components due to mechanical vibration, so that the output signal without the polarizer is called the misalignment signal in this paper. Figure 8(b) indicates the misalignment signal when a sound wave of 25 Pa and 1 kHz was applied. Unfortunately, an undesired signal of 30 mV was observed. The difference between the nominal microphone signal and the misalignment signal is, in this study, called the net microphone signal, which is produced by the normal operation of the optical microphone. From Figs. 8(a) and (b), the net microphone signal is evaluated to be 35 mV.

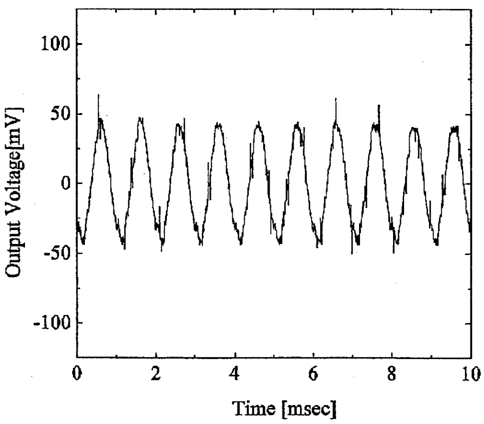
Figures 9-11 show the output voltages for the sound pressures of 20 Pa (120 dB-SPL), 8 Pa (112 dB-SPL) and 2 Pa (100 dB-SPL), respectively. The left-side figures correspond to the nominal microphone signal, and the right-side figures the misalignment signal. From these results, the net microphone signal is 31 mV for 20 Pa, 11 mV for 8 Pa, 2 mV for 2 Pa.

Figure 12 indicates the net microphone signal versus the sound pressure. It is found from the figure that the net microphone signal is almost proportional to the sound pressure. Since the noise level of the whole system was 2 mV, the minimum detectable sound pressure was evaluated to be 2 Pa, corresponding to 100 dB-SPL in sound pressure level. The minimum detectable sound pressure level was lower by more than 40 dB compared with that in the previous study.

If the optical microphone should detect normal speech, ranging from 55 to 65 dB-SPL, the S/N ratio must still be improved by a factor of more than 100. Achieving still higher sensitivity is possible by using a thinner and larger diaphragm and by enhancing the average output power.

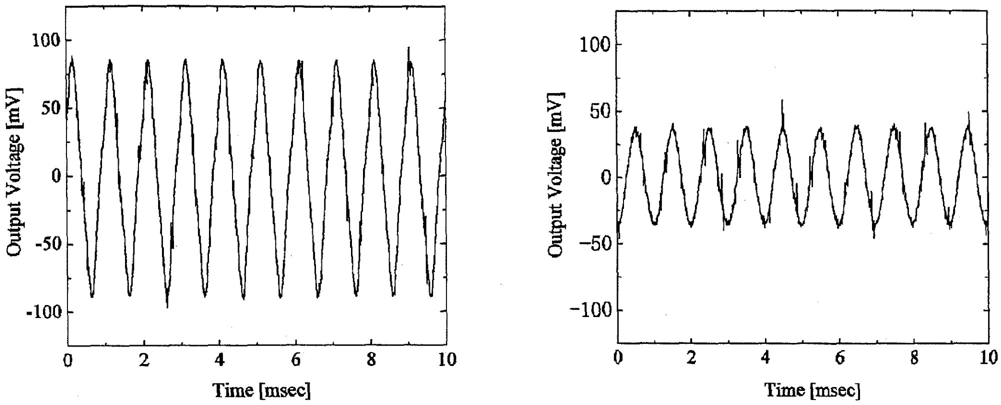


(a)



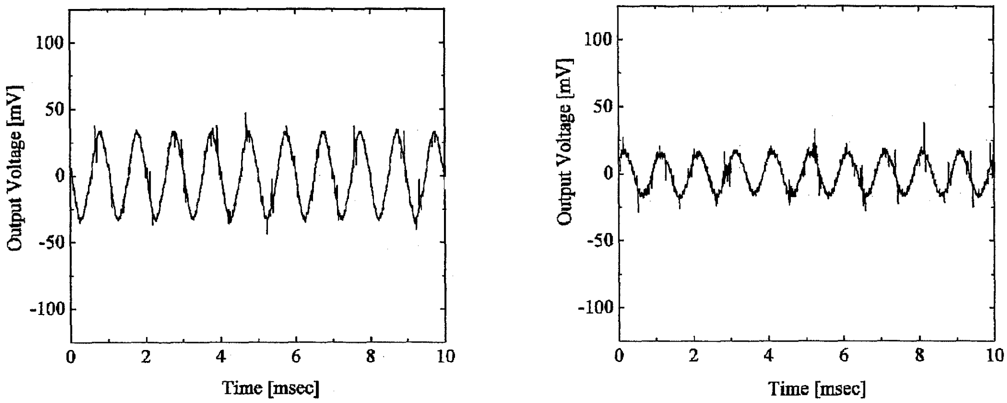
(b)

Fig. 8 (a) A nominal microphone signal (with the output polarizer), and (b) a misalignment signal (without the output polarizer) responding to a sound wave of 25 Pa and 1 kHz.



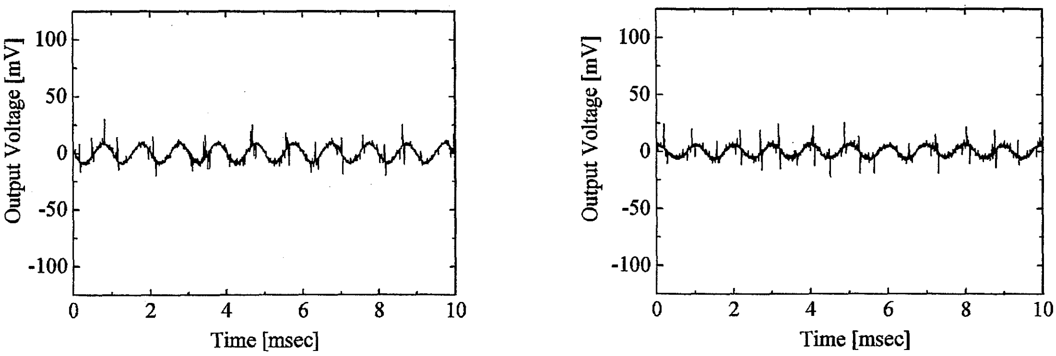
(a) (b)

Fig. 9 (a) A nominal microphone signal (with the output polarizer), and (b) a misalignment signal (without the output polarizer) responding to a sound wave of 20 Pa and 1 kHz.



(a) (b)

Fig. 10 (a) A nominal microphone signal (with the output polarizer), and (b) a misalignment signal (without the output polarizer) responding to a sound wave of 8 Pa and 1 kHz.



(a) (b)

Fig. 11 (a) A nominal microphone signal (with the output polarizer), and (b) a misalignment signal (without the output polarizer) responding to a sound wave of 2 Pa and 1 kHz.

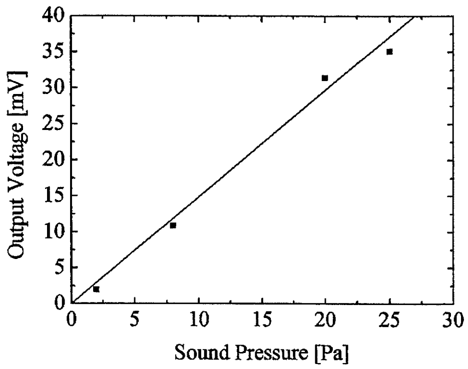


Fig 12 The net microphone output versus sound pressure

5. CONCLUSIONS

The S/N ratio of a glass-based guided-wave optical microphone was improved by a factor of approximately 100, so that an output signal from the microphone could be successfully obtained The measured net microphone signal was proportional to the sound pressure The minimum detectable sound pressure level of the fabricated microphone was experimentally evaluated to be 100 dB-SPL So, the S/N ratio of the microphone must still be improved by a factor of more than 100 in order to detect normal speech Moreover in this study, the output signal from the microphone was influenced by the misalignment of the optical components due to mechanical vibration To maintain alignment the optical fiber should be connected to one endface of the microphone as shown in Fig 1

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