Micromachined Arrayed Capacitive Ultrasonic Sensor/Transmitter with Parylene Diaphragms

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Following our previous report in which a capacitive ultrasonic sensor featuring a polymer Parylene diaphragm was developed by the micromachining technique, in the present study, an arrayed device comprising 5 x 5 sensors/transmitters was fabricated and characterized. In addition to the durability and high sensitivity due to polymer nonbrittleness and flexibility, merits attributable to Parylene, such as biocompatibility, chemical resistivity, complementary metal oxide semiconductor (CMOS) compatibility, and conformal deposition, are expected to be achieved in the future. The dispersion of sensitivity and resonant frequency of the individual sensors in the developed arrayed device was experimentally investigated. The electrical scanning of receiving directivity was performed using the arrayed device based on the delay-and-summation principle. A wide scanning angle of at least 50° was achieved. Each developed sensor was activated as a transmitter by applying an impulsive high voltage. The transmitted waveform was detectable as far as 1,000 mm away. The ultrasound was transmitted over a wide direction ranging from θ = −80° to 80°. The possibility of the electrical scanning of transmitting directivity was preliminarily confirmed using the arrayed device. [DOI: 10.1143/JJAP.47.6513]

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1. Introduction

For the external environment recognition of a robotic field, an ultrasonic sensor has advantages in cost performance compared with other sensors such as vision devices. In particular, in the spaces where vision devices cannot be used (i.e., in the dark), ultrasonic sensors are effective. For the purpose of using ultrasonic devices in microrobot applications, it is necessary to miniaturize the current ultrasonic sensors/transmitters. Using many miniaturized sensors/transmitters in an array, the electrical scanning of directivity based on the delay-and-summation principle and acoustic imaging based on the synthesis aperture principle are possible, which could be effectively used for robotic and medical applications. Miniaturizing one sensing/transmitting element is useful both for realizing an arrayed device in a limited space and for realizing a device with omnidirectional characteristics, since the directivity of each element becomes wider as its diaphragm area becomes smaller.

As an example of conventional commercially available capacitive microphones, B&K-type 4138 can receive sound pressure in the ultrasonic frequency range, and can be approximated to be nondirectional by virtue of the small area of its diaphragm. However, this microphone has the drawback of being expensive due to its complicated and precise structure, i.e., it is composed of a thin nickel diaphragm, its support rim, and a nickel backing plate facing the diaphragm surface. A capacitive ultrasonic sensor can also act as a transmitter by applying an impulsive high voltage between two electrodes, i.e., a diaphragm and a backing plate, both of which are conductive or coated by thin metal films. However, this B&K microphone is not applicable for this use because of the possibility of diaphragm fracture, taking into account its high cost.

In contrast, several studies on a capacitive microphone with a silicon diaphragm have been conducted using micromachining technology, and some of them have been commercialized. Using this technology, numerous arrayed miniaturized ultrasonic sensors with uniform performance can be fabricated on a silicon wafer with a fine resolution of several microns and a comparatively low cost, which may make it possible to fabricate an arrayed-type sensor and to activate it as a transmitter (or speaker).

In micromachined capacitive microphones, the diaphragms are generally made of a silicon-based material, such as polysilicon and silicon nitride. In a few studies a polymer material was used for the diaphragms, such as polyimide, poly(tetrafluoroethylene) (trade name: Teflon), and poly(ethylene terephthalate) (PET; trade name: Mylar). Since polymer materials have high durability due to their flexibility and nonbrittleness compared with silicon-based materials, their use in transmitters or speakers is thought to be possible. That is, the possibility of survival of a polymer diaphragm would be higher compared with that of a silicon diaphragm even when the applied high impulsive voltage for transmission passes instantaneously over the collapse voltage, at which the diaphragm is strongly pulled by an electrostatic attractive force to adhere to the substrate, causing the collapse of the device structure. Since a large displacement of the diaphragm per sound pressure is obtained due to the flexibility of the polymer diaphragm, the high sensitivity of the microphone can be realized. This is because the mechanical impedance of the diaphragm theoretically becomes low as the Young’s modulus of the diaphragm’s material decreases, provided that the radius, thickness, and input frequency are constant.

An ultrasonic transducer with a Mylar diaphragm has been commercialized (MicroAcoustic Instruments, trade name: BAT), and is often used in the ultrasonic research field; however, although the pits on the backing plate of this transducer are fabricated by micromachining technology, the polymer diaphragm film is assembled by pressing it to the backing plate with adequate pre-tension using a holder, the assembly of which appears as complicated as that of the above-mentioned B&K-type 4138 microphone.
Polyparaxylylene (trade name: Parylene) is one of the polymer materials expected to be applied in the polymer micro-electro-mechanical-systems (MEMS) field. The deposition of Parylene is based on chemical vapor deposition (CVD), which is suitable for MEMS diaphragm fabrication. The mechanical properties of silicon, silicon nitride, Parylene, and Mylar are compared, as shown in Table 1. In addition to its flexible and nonbrittle characteristics compared with common polymer materials, Parylene has several excellent characteristics as follows: 1) It is a biocompatible material, which allows medical applications of the device. 2) It is chemically stable, i.e., it has high resistivity to acid, base, and organic solvents, which protects the device from external chemical environments. 3) It has high complementary metal oxide semiconductor (CMOS) compatibility compared with other polymer materials, since it can be deposited at room temperature. This characteristic makes the integration of a device with electrical circuits possible; such a device is called a smart device. 4) Its CVD deposition is conformal, thus the deposition of a dome-shaped diaphragm is possible, which is effective for realizing a real spherical sound source/receiver. Due to these characteristics, an ultrasonic device utilizing a Parylene diaphragm has great potential in future applications.

The first report of the application of this material to the diaphragm of an ultrasonic sensor has been produced by the authors, the details of which were reported in ref. In this report, one Parylene sensor, i.e., not an array type, was fabricated and its receiving performance was characterized, which is summarized as follows: it can receive an impulsive ultrasonic pulse transmitted by an electric spark discharge with an open-circuit sensitivity of 0.3 mV/Pa. A well-damped waveform is obtained by setting appropriate acoustic holes. A ranging system using this sensor can measure a distance of up to 1 m with an error of less than 1 mm based on time-of-flight measurement. The developed sensor can receive ultrasound over a wide direction, which ranges from $\theta = -80^\circ$ to $80^\circ$, i.e., the developed sensor can be approximated to be nondirectional.

Following our previous report, here we report the development of a Parylene arrayed ultrasonic device composed of many sensors, which is effective for the electrical scanning of receiving directivity based on the delay-and-summation principle. We also report that each developed sensor can act as a transmitter by applying a high impulsive voltage, which means that the scanning of transmitting directivity is also possible. Finally, the scanning performance of the developed Parylene arrayed sensors/transmitters is experimentally characterized.

## 2. Development of Parylene Arrayed Ultrasonic Device and Experimental Setup for Characterizing Receiving Performance

### 2.1 Fabrication process

The authors have developed an ultrasonic sensor with a Parylene diaphragm using micromachining technology. An overview and schematic cross section of the fabricated sensor are shown in Fig. 1.

The sensor was fabricated by depositing Parylene (2 μm in thickness) on a Si wafer (150 μm) with a thermally grown oxide (1 μm). Aluminum was sputtered to form the lower electrode (0.2 μm) and upper electrode (0.5 μm). The Parylene diaphragm was released by etching away the sacrificial layer of amorphous silicon (1.5 μm, deposited by plasma-enhanced CVD) using XeF$_2$ gas. Namely, the height of the cavity was 1.5 μm, which is thought to be sufficiently large to prevent the diaphragm from collapse even when a high impulsive voltage is input during the transmission.

The backside of the silicon wafer was dry etched by inductively coupled plasma deep reactive ion etching (ICP-DRIE) to produce acoustic holes, which control air damping. These holes also act as the etching holes for the sacrificial amorphous silicon layer, inside which XeF$_2$ etching gas was introduced.

### Table I. Comparison of mechanical properties of silicon and polymer materials.

| Material       | Young's modulus (GPa) | Shear modulus (GPa) | Density (kg/m$^3$) | Poisson ratio |
|----------------|-----------------------|---------------------|--------------------|--------------|
| Silicon        | 131                   | 80                  | 2.330              | 0.27         |
| Silicon nitride | 390                   | 110                 | 3.290              | 0.27         |
| Parylene       | 3.2                   | —                   | 1.287              | 0.4          |
| PET (Mylar)    | 2.8                   | —                   | 1.370              | 0.4          |

a) Crystal silicon in (100) plane.

b) LP CVD Si$_3$N$_4$.

— Not clarified.

Fig. 1. Overview and cross section of one sensor. Amorphous silicon is used as a sacrificial layer, which is dry-etched away by XeF$_2$. The radius and number of acoustic holes are determined by FEM in order to achieve adequate damping.
2.2 Damping issue

In several ultrasonic sensors such as capacitive micro-
machined ultrasonic transducers (cMUT), the etching
holes set on the diaphragm are finally plugged in a vacuum
by depositing the same material as that of the diaphragm,
achieving the vacuum condition inside the cavities. In this
case, the damping is only due to the internal friction of the
diaphragm material; thus, the possibility exists that the
damping may be insufficient, particularly for airborne
applications, in which viscous damping due to liquid water
does not occur. In contrast, the damping of the proposed
sensor is mainly due to air damping, the effect of which is
much larger than that of the internal friction.

As one of the purposes of this study, an ultrasonic ranging
system for airborne use has been proposed by the authors,
which measures the time-of-flight of an ultrasonic pulse. In this system, the first peak of the pulse waveform is
detected by setting an appropriate threshold level. The first
zero-cross point after the first peak is regarded as the arrival
time of the ultrasonic pulse. The important point in this
system is that the pulse waveform is well-damped even in
the less viscous airborne use, so that all the peaks on and
after the second peak are smaller than the first one, which is
important for detecting the first peak with certainty. In this
study, the damping ratio is \( \frac{1}{\sqrt{2}} = 0.707 \), which is the
critical value at which the peak does not appear in the
frequency response of the amplitude, realizing a well-
damped waveform with a broad bandwidth. The authors
have investigated the radius of the acoustic hole and the
number required to achieve this value of damping ratio by
both FEM simulation and experiments. Considering these
circumstances, the acoustic holes are employed in this study;
however, in the immersion application, i.e., hydrophone use,
sealing the cavity of the Parylene transducer in a vacuum
would be useful, which is a planned future study.

2.3 Development of arrayed device and detecting circuitry
for capacittance change

In this study, an arrayed device comprising 5×5 developed sensors was fabricated. A photograph and its actual
size are shown in Fig. 2. The specification of one sensor in the array is as follows: the radius \( R_a \) of the diaphragm
is 1,200 μm, its thickness is 2 μm, the distance between
adjacent diaphragms \( d \) is 3,000 μm, the radius of the acoustic hole \( r \) is 60 μm, and the number of holes \( n \) is 121.

The length of wiring is different for each sensor, causing different wiring resistances; examples of the theoretical
values of which are shown in Table II. In this table, the wiring length for sensor no. 3 is the minimum and that for
sensor no. 13 is the maximum among all the sensors. The
time constant of \( T_m = CR \), which is calculated using the
resistance \( R \) in this table and the measured capacitance \( C \) (it
is approximately 30–70 pF as later shown in Table III), is
approximately nanosecond order. Thus, the delay time due
to wiring length does not have any effect on the procedure of
electrical scanning of receiving directivity, the method and results of which are described in §2.5 and §3.3, respectively.

The circuitry used to detect the capacittance change due to the diaphragm displacement caused by ultrasonic sound
pressure is documented herein. A bias voltage of 100 V was
applied to the fabricated Parylene capacitive sensor. This value has an effect on the sensitivity, resonant frequency,
and bandwidth. In this study, this value is defined on the basis of values in references, in which 150 V, 100 V, 100–400 V,
and 50–135 V were employed. In this study, the values of 150 and 200 V were also experimentally
tested; however, it was observed that the diaphragm was broken when a high impulsive voltage of 700 Vpp was applied during the transmitter use (the detail of which is explained in §4), although this failure rate is small. Thus, considering the safety factor, the value of 100 V was employed, under which condition neither diaphragm failure nor the disconnection of wiring was encountered.

Upon being supplied with a constant electrical charge due to the bias voltage, the diaphragm displacement was transformed to the voltage change at the sensor’s electrode, and it was amplified by a factor of 30 (29.5 dB). The circuitry used for the capacitance-to-voltage (CV) transformation and the amplification is shown in Fig. 3, in which the high-frequency component of the voltage change is extracted by a bias-cut condenser, and it is input to an operational amplifier (op-amp) by a shunt resistor. Only the range within ±0.7 V is dealt with for amplification by virtue of a voltage limiter using two diodes, considering noise reduction.

2.4 Experimental setup for characterizing receiving performance

The experimental setup for characterizing the receiving performance of the developed sensor is schematically shown in Fig. 4(a). An electric spark discharge was used as an ultrasonic transmitter. Transmitted ultrasound is impulsive, the power spectrum of which is distributed over a broad frequency range.26 The developed Parylene sensor was set on a rotational table. The distance between the transmitter and the center of the arrayed sensor was set to 150 mm to characterize the performance of one sensor (the results
are described in §3.1, and 130 mm to perform electrical scanning of the arrayed sensor (details of the conditions are described later in §2.5 and the results are described in §3.2 and §3.3). The ultrasonic wave is approximated to be a plane wave at the sensor position, after progress from the transmitter, where it is approximately a spherical wave. As a reference, a microphone to estimate the sound pressure at the same position where the sensor was set, B&K type 4138 (already detailed in §1) was used.

2.5 Experimental method of electrical scanning of receiving directivity

Five sensors lying in one line were selected from the developed arrayed device, and they were used for an experiment involving the electrical scanning of receiving directivity. The experimental conditions are schematically shown in Figs. 4(b) and 4(c). The fabricated arrayed device was rotated using a rotational table. Let the rotational angle be \( \theta \). Then the difference of sonic path length for two adjacent sensors is expressed as \( a \sin \theta \), where \( a \) is the interval between the sensors (\( a = 3,000 \mu \text{m} \) in this case).

The procedure, based on the delay-and-summation principle, is as follows. Received pulse waveforms for the five sensors are schematically shown in Fig. 5(a). Their arrival times have differences based on the differences in sonic path length. After recording the waveforms in a computer, the positive peak of each waveform is detected. Taking this peak as the center, a rectangular pulse wave with 5 \( \mu \text{s} \) width is generated, as shown in Fig. 5(a). Then, each pulse is shifted by a delay time of \((n - 1) \cdot a \sin \alpha / v\), where \( \alpha \) is the scanning angle of directivity, \( v \) is the sound velocity (343.6 m/s is employed in this experiment), and \( n \) is the number of the sensor (1, 2, … , 5). The shifted pulses are summed, and the area inside the width of pulse no. 1 is extracted from the summed result, which is the hatched area shown in Fig. 5(b). The average height of this area is estimated as the index of sensitivity. Examples of actual summed rectangular waveforms are shown in Fig. 5(c). Looking at this figure, the width of the summed result almost coincides with that of pulse no. 1, i.e., it almost fits inside a 5 \( \mu \text{s} \) width in the case of \( \alpha = \theta \), while it does not do so in the case of \( \alpha \neq \theta \). Namely, the sensitivity is maximized in the former case.

These processes, i.e., detecting peaks, generating pulses, shifting them, summing them, and extracting the area for estimation, were performed by developed computer software. In the experiment, \( \theta \) was set at 0, 10, ,… , 80°. For each \( \theta \), a scanning angle \( \alpha \) of 0, 10, ,… , 80° was tested computationally, and the sensitivity of each combination of \( \theta \) and \( \alpha \) was estimated.

3. Receiving Performance of Developed Parylene Ultrasonic Device

3.1 Sensitivity and resonant frequency of one sensor

An example of an ultrasonic pulse waveform received by one sensor is shown in Fig. 6(a). As already reported in ref. 25, the open circuit sensitivity was estimated to be 0.3 mV/Pa using a B&K-type 4138 reference microphone. High sensitivity, the order of which is comparable with that of the B&K microphone (0.9 mV/Pa), was achieved.

In this study, the resonant frequency is defined as the reciprocal of the period between the first negative peak and the second one of the received waveform in a time domain, as shown in Fig. 6(b). An example of the power spectrum of the received waveform is shown in Fig. 6(c), which is obtained using a fast Fourier transform (FFT) analyzer for the waveform shown in Fig. 6(a). The resonant frequency measured in Fig. 6(a) based on the definition shown in Fig. 6(b) coincides well with the peak frequency in Fig. 6(c), which is 43 kHz in the case of the sensor used.
3.2 Dispersion of individual sensors’ properties in arrayed device

The capacitance \(C\), the dissipation factor \((\tan \delta)\), and the impedance \((Z)\) of individual sensors were measured using an LCZ meter (NF type 2341), examples of which are shown in Table III. Considering each sensor has a small \(C\) of 30 – 70 picofarads, a comparatively high frequency \((f)\) of 100 kHz was adopted as the measuring frequency in order to increase the measuring accuracy of \(C\) and \(Z\).\(^{29}\) According to the data in this table, the resistance of one sensor due to both the wiring and the upper electrode, which is estimated as \(Z \cdot \sin \delta\), is several hundred ohm. This estimated resistance is larger than the theoretical resistance of wiring \((R)\) in Table II, since the diaphragm area is much larger than that of the wiring. However, the time constant \(T_m = CR\) is still of sub-microsecond order, the delay time due to which is negligible in the procedure of electrical scanning of directivity.

The distribution of sensitivity of individual sensors in the developed arrayed device was estimated, where the peak voltage of the received ultrasonic waveform is taken as the index of the sensitivity. The experimental results are shown in Fig. 7(a), the values of which do not strongly contradict the anticipated value of 67 mV.\(^{25}\) There is dispersion of experimental sensitivity; however, it is not significant. Thus, the first zero-cross point of the received pulse waveform\(^{25}\)
can be detected in all the sensors by setting an appropriate threshold level, i.e., the time-of-flight measurement of ultrasound for determining the distance can be generally performed for all the sensors.

The distribution of the resonant frequency of individual sensors was also estimated. The experimental results are shown in Fig. 7(b), the values of which do not strongly contradict the target value of 43 kHz [confirmed by both FEM simulation and experiments in ref. 25. Also, see Fig. 6(c)]. However, the uniformity of resonant frequency is unsatisfactory.

One reason for the dispersion of resonant frequencies is due to the fabrication, i.e., the Young’s modulus, thickness, and the intrinsic tensile stress of the Parylene diaphragm were not uniform all over the fabricated arrayed sensor area, since it is difficult to keep the process conditions strictly the same irrespective of the position inside the arrayed device. Because of this problem, the resonant frequency varied from one sensor to another, because the resonant frequency depends on these mechanical parameters.13,25) The process uniformity should be improved in future studies.

### 3.3 Electrical scanning of receiving directivity

The results of the experiment to characterize the electrical scanning performance of receiving directivity are shown in Fig. 8. In this figure, each data is normalized to a relative value in dB units, so that the sensitivity when \( \alpha = \theta \) is 0 dB. The absolute value of the sound pressure level (SPL) for the case of 0 dB for each \( \theta \) angle is shown in Table IV. Looking at this table, the SPL does not decrease as \( \theta \) increases, i.e., it takes almost the same value irrespective of \( \theta \).

According to Fig. 8, the sensitivity is increased when \( \alpha = \theta \), i.e., when the scanning angle (\( \alpha \)) is coincident with the angle of direction of the transmitter (\( \theta \)), except for only the two cases of \( \theta = 70^\circ \) and \( 80^\circ \). Even in these two cases, the error is small, within 10\(^\circ\). Note that when \( \theta \) is in the range from 0 to 50\(^\circ\), a sharp peak of directivity at the target scanning angle is obtained, which may be effective for detecting an angle at which a target object exists in microrobot applications. To conclude, it was proven that the directivity can be scanned electrically based on the delay-and-summation principle using the fabricated Parylene diaphragm.

**Table IV. Sound pressure level (SPL) for 0 dB case in Fig. 8 for each \( \theta \).**

| \( \theta \) (°) | SPL (dB) |
|-----------------|----------|
| 0               | 152      |
| 10              | 150      |
| 20              | 145      |
| 30              | 148      |
| 40              | 142      |
| 50              | 147      |
| 60              | 145      |
| 70              | 141      |
| 80              | 140      |

Fig. 8. Results of electrical scanning of receiving directivity using arrayed sensor. \( \theta \): True angle of direction of transmitter. \( \alpha \): Scanned angle of directivity. Each data is normalized, so that the sensitivity when \( \alpha = \theta \) is 0 dB. It is shown that the sensitivity from the \( \theta \) direction is intensified by setting a delay time of \( t = \alpha \cos \theta/v \): (a) \( \theta = 0^\circ \), (b) \( \theta = 10^\circ \), (c) \( \theta = 20^\circ \), (d) \( \theta = 30^\circ \), (e) \( \theta = 40^\circ \), (f) \( \theta = 50^\circ \), (g) \( \theta = 60^\circ \), (h) \( \theta = 70^\circ \), and (i) \( \theta = 80^\circ \).
arrayed device. It was also proven that a wide scanning angle of at least 50° can be achieved. This omnidirectional characteristic is due to the wide directivity of the individual sensor, which was already characterized in ref. 25.

In the case of a continuous wave, a grating robe theoretically emerges in the directivity when the interval between the sensors $a$, see Fig. 4(c) is larger than the wavelength ($\lambda$). In the fabricated sensor, this condition does not hold true since $a = 3$ mm and $\lambda = \frac{v}{f} = 8$ mm, where $v = 344$ m/s and $f = 43$ kHz. Moreover, in this study, not a continuous but a well-damped pulse wave is used, in which the amplitude intensification of waveforms due to their phase differences is sufficiently negligible. Thus, the grating robe does not emerge theoretically, which does not contradict the results shown in Fig. 8.

4. Experimental Setup for Characterizing Transmitting Performance

4.1 Transmitting circuitry

Because of the flexibility and durability of Parylene, one capacitive sensor with a Parylene diaphragm can also be used as a transmitter by applying a high impulsive voltage. A transmitting circuit was developed, as shown in Fig. 9(a), in which the same bias voltage of 100 V as that used in the receiving circuitry is employed. When the transistor is triggered, a condenser $C_T$ of 0.1 $\mu$F is discharged and an electric current is instantaneously supplied to the primary side of the ignition coil. Then a high impulsive voltage is generated at the secondary side of this coil, as shown in Fig. 9(b), which exhibits a peak-to-peak voltage of approximately 700 Vp-p (the positive voltage of 400 Vp and negative one of 300 Vp, both of which are values relative to the bias voltage of 100 V). The power spectrum of this voltage is shown in Fig. 9(c). In this figure, the peak frequency is 310 kHz, which is far larger than the resonant frequency of the developed device (43 kHz). This fact indicates that the response of the diaphragm’s displacement at the transmission can be approximately regarded as an impulse response, on which the resonant frequency of the diaphragm has a large effect rather than the peak frequency of the input voltage.

Since voltage is boosted by the ignition coil in this circuit, the small capacitance $C_T$ is sufficient for actuating the diaphragm. Thus, the charging time is comparatively short and the frequency of transmitting can be set at more than 100 Hz.

4.2 Experimental setup for characterizing transmitting performance

The transmitting performance of the developed Parylene device was characterized. The experimental setup is schematically shown in Fig. 10. The device was set on a rotational table. Each sensor in the arrayed device was activated as a transmitter. In addition to the arrayed device, a device including several sensor/transmitters with different radii of the diaphragm and different radii of the acoustic hole was prepared. This device was used to investigate the effect of the area of the diaphragm on the transmitted sound pressure (results are shown in §5.2) and the effect of the acoustic holes on damping of the transmitted waveform (results are shown in §5.3).

The B&K-type 4138 reference microphone (with sensitivity 0.9 mV/Pa) was used as a receiver. The distance between the center of the arrayed transmitter device and the receiver was set to several values ranging from 10 to 1,000 mm to characterize the performance of one transmitter (the results are described in §§5.1–5.4), and 40 mm to perform the electrical scanning of the arrayed transmitter.

Fig. 9. Transmitting circuitry for generating a high impulsive voltage: (a) circuitry, (b) impulsive high-voltage input to each sensor, and (c) its power spectrum.
In the case that the transmitted acoustic pressure is small, the received signal obtained by the reference microphone was amplified by a factor of 3,000 (69.5 dB) using an instrumentation amplifier (ACO type 6030).

4.3 Experimental method of electrical scanning of transmitting directivity

Five collinear transmitters were selected, and they were used for an experiment involving the electrical scanning of transmitting directivity. The experimental conditions are schematically shown in Fig. 11(a). The fabricated arrayed device was rotated using a rotational table. Let the rotational angle be \( \theta \). Then the difference of the sonic path length for two adjacent transmitters is expressed as \( a \sin \theta \), where \( a \) is the interval between the transmitters.

The procedure, based on the delay-and-summation principle, is as follows. Trigger input pulses for the five transmitters are schematically shown in Fig. 11(b). When the frequency of these pulses is set to \( f = \nu / (a \sin \alpha) \), the transmitted waves are theoretically intensified in the \( \alpha \) direction, where \( \alpha \) is the scanning angle of directivity, and \( \nu \) is the sound velocity (343.6 m/s is employed in this experiment).

For each \( \theta \), the scanning angle \( \alpha \) is set by changing the frequency of input trigger pulses \( f \). The peak voltage of waveform, which is received by the B&K microphone, is estimated.

5. Transmitting Performance of Developed Parylene Ultrasonic Device

5.1 Transmitted pulse waveform and detectable distance

The ultrasonic waveform, which is emitted by the developed transmitter and received by the B&K-type 4138...
reference microphone, is shown in Fig. 12(a). The acoustic pressure obtained at a distance of 10 mm was 13 Pa, which is rather small. Therefore, the signal was amplified using an instrumentation amplifier as mentioned in the previous section. The amplified received waveform obtained at a distance of 150 mm is shown in Fig. 12(b). By this amplification, the maximum distance at which the transmitted waveform is detectable was extended. The experimental results of the relationship between the distance and the peak voltage of the transmitted waveform are shown in Table V, which indicates that the transmitted waveform can be detected as far as 1,000 mm away by setting an appropriate threshold level. It was confirmed that the developed transmitter is useful for the application of ranging the distance based on the time-of-flight measurement in the air, such as external environment recognition in the robotic field.

5.2 Effect of diaphragm area on transmitted sound pressure

The pulse waveforms emitted by the developed transmitters, of which the diaphragm radii are 500, 700, 900, and 1,200 µm, were obtained, and their peak voltages were transformed to the sound pressure. The relationship between the diaphragm area and the transmitted sound pressure at 150 mm distance is shown in Fig. 13. It was proven that the sound pressure increases proportionally with the diaphragm area.

5.3 Effect of acoustic holes on damping of transmitted waveform

The authors have theoretically investigated the effects of the radius of the acoustic hole $r$ and the number of holes $n$ on the diaphragm’s damping ratio $\zeta$. It was proven that $\zeta$ is inversely proportional to $r$ and $n$, which was also experimentally confirmed by the ultrasonic waveform received by the developed sensor. In this section, we aim to confirm this effect of acoustic holes by the ultrasonic waveform emitted by the developed transmitter.

The developed transmitters with different sizes of acoustic holes, of which diaphragm radius is 1,200 µm, were employed. The radii of the acoustic holes $r$ are 80, 75, 55, and 50 µm. The ultrasonic pulse waveforms emitted are shown in Figs. 14(a)–14(d). The distance was set to 10 mm, and the waveform was detected by the B&K microphone with no amplification. Note that a second small waveform is also observed in this figure, which is reflected by the B&K microphone, returns to the transmitter, reflected by the transmitter, and again returns to the microphone.

According to this figure, a well-damped transmitted waveform is obtained when $r$ is 55 or 50 µm, whereas a residual vibration is seen when $r$ is 80 or 75 µm. Namely, it was confirmed that $\zeta$ is inversely proportional to $r$. The effect of acoustic holes on the diaphragm damping confirmed here using the transmitted waveform does not contradict that confirmed using the received waveform in the authors’ previous report.

5.4 Directivity of one transmitter

The directivity of the developed transmitter was estimated using the experimental setup shown in Fig. 10. The distance between the transmitter and the sensor was set to 150 mm, and the peak voltage of the received pulse waveform was estimated by changing the angle of the transmitter using a rotational table. Results are shown in Fig. 15. From these results, the directivity becomes wide as the diaphragm radius decreases. It was confirmed that both of the transmitters used in this experiment can emit ultrasound over a wide direction, which ranges from $\theta = -80$ to $80^\circ$, with an attenuation level
of less than $-4 \text{ dB}$ compared with the case where $\theta = 0^\circ$. Namely, the developed transmitter can be approximated to be nondirectional. This wide transmitting directivity was effective for realizing the omnidirectional characteristics of the arrayed device, which is investigated in the following section.

5.5 Electrical scanning of transmitting directivity

First, the crosstalk between adjacent transmitters was measured. When one transmitter is triggered by an applied input voltage of $700 \text{ V}_{\text{pp}}$, a voltage of $1.2 \text{ V}_{\text{pp}}$ was then observed at the adjacent transmitter, which was $0.17\%$ noise. Thus, the effect of the crosstalk on the transmitting directivity is thought to be negligible.

The results of the experiment to characterize the electrical scanning performance of transmitting directivity are shown in Fig. 16. In this figure, each data is normalized, so that the detected peak voltage when $f = v/(a \sin \theta)$, i.e., $\alpha = \theta$, is $0 \text{ dB}$. According to this figure, the transmitted waveform was intensified at $f = v/(a \sin \theta)$, i.e., it was intensified when the scanning angle ($\alpha$) was coincident with the angle of the direction ($\theta$) of the transmitter. However, the directivity when $\theta = 30^\circ$ [see Fig. 16(a)] was less sharp than that in the other conditions in this figure. The same tendency of directivity was obtained when $\theta = 0$, 10, 20, and 80$^\circ$ (data were omitted). This may be caused by an experimental problem, the improvement of which is a possible future study. To conclude, although further study is necessary, the possibility of controlling the transmitting directivity was preliminarily shown in this experiment using the fabricated arrayed device.

6. Conclusions

An arrayed device comprising $5 \times 5$ ultrasonic sensors/transmitters featuring polymer Parylene diaphragms was fabricated, and its performance was characterized. In addition to the durability and high sensitivity due to polymer nonbritleness and flexibility, merits attributable to Parylene, such as biocompatibility, chemical resistivity, CMOS compatibility, and conformal deposition, are expected to be achieved in the future.

Following the previous report by the authors in which one ultrasonic Parylene sensor, i.e., receiver, was fabricated, the contents of this study are briefly summarized as follows. 1) An arrayed ultrasonic device was developed by the micromachining technique. The dispersion of individual sensors’ properties, i.e., the sensitivity and the resonant frequency, was experimentally investigated. 2) The electrical scanning of receiving directivity was performed on the basis.
of the delay-and-summation principle. A wide scanning angle of at least $50^\circ$ was achieved. 3) Each developed sensor was activated as a transmitter by applying a high impulsive voltage. The transmitted waveform was detectable as far as 1,000 mm away. The ultrasound was transmitted over a wide direction ranging from $\theta = 30^\circ$ to $80^\circ$. 4) The possibility of electrical scanning of transmitting directivity was preliminarily confirmed using the developed arrayed device. By scanning both the transmitting directivity and the receiving directivity of the developed arrayed device, detecting the direction in which objects or obstacles exist is a future study. In this study, by detecting the time-of-flight of an ultrasonic pulse reflected by objects or obstacles, the distance from them is also detectable. By using the information on both the direction and the distance, the positions of objects or obstacles may be obtained in the future. Further quantitative investigation of the merits of the developed Parylene ultrasonic arrayed sensors/transmitters compared with other reported silicon or polymer devices is also a planned future study.

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