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# Intensifying Thermally Induced Ultrasound Emission

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## Abstract

In a recent research, a new method of ultrasound emission was proposed. Though thermally induced ultrasound (TIU) emission proposed there has some notable features, the sound intensity and efficiency was very low in that report. In this paper we show methods to enhance the power and efficiency of TIU. The acoustic intensity can be heightened to be more than 1 kPa, and we can expect a non-contact actuator that gives manipulation force using radiation pressure. The most important key of the enhancement is concentrating electrical power both spatially and temporally. We show the principle and experimental results including radiation pressure generation.

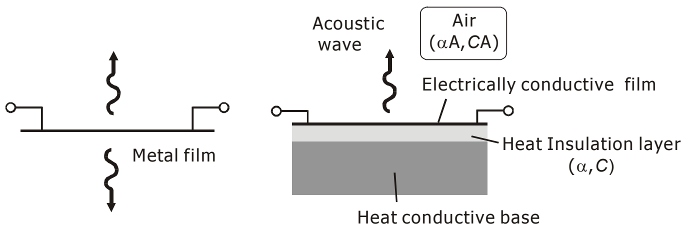
Key words: *thermally induced ultrasound, radiation pressure, non-contact actuator*

## 1. Introduction

Among the vast amount of researches and products to generate ultrasound in the air, most of them are based on the transmission from vibration of solid to the air [1]. In 1999, we proposed a new principle of airborne ultrasound device based on thermal inducement [2]. The device has some attractive features as follows. The frequency characteristic is ideally flat. Then very high frequency sound can be generated without distortion. The structure is simple and it has no movable parts. When we integrate small ultrasonic emitters into an array, we do not have to worry about interference among the sites.

In the former report, however, the intensity of the generated sound was only 0.1 Pa while prevailing transducers transmit 10-Pa ultrasound. In addition, the efficiency from electrical power to sound power was as small as $10^{-9}$. In this paper we describe how we can enhance the sound power and the efficiency. And we show the intensity of thermally induced ultrasound (TIU) can be heightened as strong as 10 kPa potentially, and that a very small and strong sound beam emitter can be realized.

The aim of this research is developing a new device using non-linear effect of ultrasound for various applications. For example, it is known that intense ultrasound produces 'radiation pressure' on the object surface within the beamed spot. Therefore such a narrow beam of ultrasound can be 'a non-contact actuator' that provides manipulation force using the radiation pressure. In the following sections, we show the principles of high power ultrasound emission and experimental results including radiation pressure generation.




(a) Thermophone (b) Our TIU device

**Fig. 1:** Comparison between 'thermophone' and our TIU device.

## 2. Thermally Induced Ultrasound Emission

Basic structure of TIU emitter is shown in **Fig. 1**. The device consists of three layers. The top layer is a thin, electrically conductive film that is used for generating Joule's heat. The middle layer is a heat insulation layer with low thermal conductivity and low heat capacity per unit volume. To understand the roll each part plays, we should compare it with 'thermophone' proposed in the early 20th century [3]. In both principles, ultrasound is generated by thermal expansion by Joule's heat from the conductive film. An air layer on the device surface with thickness

$$D_{\mathrm{A}}(\omega) = \sqrt{\frac{\alpha_{\mathrm{A}}}{C_{\mathrm{A}}\omega}} \tag{1}$$

follows the temperature of the device surface where $\alpha_{\mathrm{A}}$ and $C_{\mathrm{A}}$ are the heat conductivity and the heat capacity per unit volume of the air, respectively. The $\omega$ is a temporal frequency (angular velocity) we are concerned about. The $D_{\mathrm{A}}$ at 100 kHz is 5 $\mu$m at 300 K and under atmospheric pressure. The expansion of this air layer generates the acoustic wave.

The aim of the thermophone's structure is to heat the air. Unfortunately, however, even very thin film of 1 $\mu$m has more than 100 times larger heat capacity than that of the air layer at 100 kHz, for example. Then the most of the power is used for heating the metal film rather than the air. Another problem is the poor heat pass to remove accumulated heat in the film. Since the Joule's heat gives only positive power to the film, the temperature of the film easily increases.

Our TIU device resolves these problems by the 3-layer structure. Suppose, tentatively, an electrically conductive layer is located on a sufficiently thick insulation layer. If we drive the conductive film at $\omega$, the depth of the insulation layer that follows the surface temperature at frequency $\omega$ is

$$D(\omega) = \sqrt{\frac{\alpha}{C\omega}}\ , \tag{2}$$

where $\alpha$ and $C$ are the heat conductivity and the heat capacity per unit volume of the insulator, respectively. Therefore replacing the part of the insulator deeper than $D$ with heat conductive material causes no amplitude loss of surface temperature change at frequency $\omega$, while it suppresses the stationary temperature to rise up to the comparable amount to alternative temperature change. Another merit is that we can virtually decrease the heat capacitance of the sounder at high frequency. If we generate 10-MHz ultrasound, the $D$ is estimated at 0.15 $\mu$m using porous silicon as described in [2]. Then the thickness of aluminum film that has the same heat capacitance as the 0.15 $\mu$m porous silicon is only 40 nm.

As regards our TIU device, relationship between the Joule's heat $q(\omega)$ [W/m$^2$] given on the surface and acoustic pressure $P(\omega)$ [Pa] from the device surface is written as

$$P(\omega) = A\frac{1}{\sqrt{\alpha C}}q(\omega)\,, \tag{3}$$

$$A = \sqrt{\frac{\gamma\alpha_{\mathrm{A}}}{C_{\mathrm{A}}}}\frac{P_A}{vT_A} \tag{4}$$

when the device size is sufficiently larger than the wavelength of the generated sound.
The $v$, $P_{\mathrm{A}}$, and $T_{\mathrm{A}}$ are respectively the sound velocity, the atmospheric pressure, and the room temperature [2]. The $\gamma$ is equal to $C_{\mathrm{p}}/C_{\mathrm{v}} = 1.4$.

An important feature here is that acoustic pressure is proportional to input electrical power. Using this property we show methods to enhance sound power.

## 2. High Power TIU Emission

In this section we discuss methods to obtain high power of acoustic wave from a TIU device. The aim of this argument is applying the TIU to a device using a non-linear effect of ultrasound. First obvious approach is developing material with smaller $\alpha C$ in Eq. (3). In the following section, however, we discuss essences apart from the material properties.

As mentioned in above section, one interesting feature is that sound pressure is proportional to input power. Because the acoustic power emitted from the device is written as

$$J = \frac{P^2}{\rho_A v}, \tag{5}$$

the efficiency from electrical power to acoustic power is proportional to input power ($\rho_{\mathrm{A}}$ and $v$ are the density of the air and the sound velocity of the air, respectively).

Therefore we can derive the following fundamental principles to obtain high acoustic power.

### 2.1 Spatial concentration

Suppose that our device area is $S$, and we give total power $Q$ [W] to the sounder, and uniform plane wave is emitted from the area (this means that the sound wavelength is smaller than the device size). Then the acoustic pressure is written as

$$P(\omega) = B\frac{Q(\omega)}{S} \tag{6}$$

using a constant $B$. Therefore the total acoustic power emitted from the device is given as

$$J = S\frac{P^2}{\rho_A v_A} = \frac{B^2}{\rho_A v_A}\frac{Q^2}{S} \quad . \tag{7}$$

Therefore total output power is proportional to $1/S$. We can get larger sound power from smaller $S$ for constant total power consumption.

### 2.2 Temporal concentration

Since TIU sound pressure is proportional to input power, a temporally localized electrical input causes a temporally localized acoustic emission.

We show two kinds of signal pattern that consume the same amount of total energy in **Fig. 2**. The figure (a) shows a signal with constant amplitude. Meanwhile the figure (b) is a temporally localized signal. Suppose we write the average acoustic power by the signal pattern (a) as

$$J_1 = B' Q_0^2 \tag{8}$$

using a constant $B'$. Then the average acoustic power in the case (b) is given as

$$J_2 = aB'\left(\frac{Q_0}{a}\right)^2 = \frac{J_1}{a} \,. \tag{9}$$

Therefore the average acoustic power is proportional to the concentration factor $1/a$.

It would be helpful to show an example demonstrating the effectiveness of these two kinds of concentration. In the former paper [2], we reported that our 1 $cm^2$ device could generate 0.1 Pa by 1 W. If we concentrate the same average power into 1 $mm^2$ area with a temporal concentration $a = 0.01$, the average effective value of the radiated acoustic pressure reaches 100 Pa.

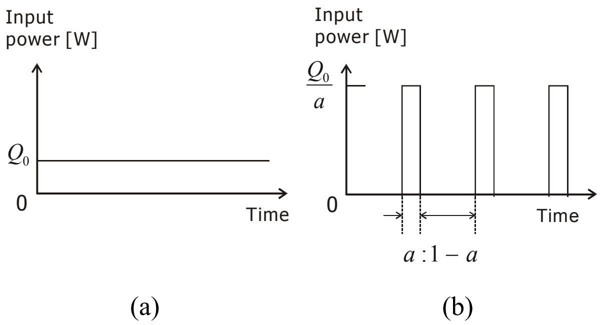



**Fig. 2:** Explanation of temporal concentration.

## 3. Other factors to be considered

The above section's theory showed the power concentration in time and space improves the maximum power and efficiency of TIU emission. Practical limits of the improvement and other related factors are considered in this section.

### 3.1 Temperature and electromigration

The smaller the $a$ in **Fig. 2** becomes, the larger the momentary temperature rises. As regards TIU device, the relationship between surface temperature and input power is given as [2]

$$T(\omega) = \frac{q(\omega)}{\sqrt{j\omega\alpha C}} \,. \tag{10}$$

Then increase of the frequency brings the decrease of the temperature amplitude so as to be proportional to $1/\sqrt{\omega}$. Since the relationship between $P(\omega)$ and $q(\omega)$ in Eq. (3) does not depend on the frequency, a higher-frequency driving signal with thinner insulator layer can suppress the temperature rise for the same acoustic power output.

For example, If we consider 100 kHz signal, we obtain a relationship $T$ [K] = 0.2$P$ [Pa]. Then for intense sound $P$ = 10 [kPa], the $T$ reaches 2,000 K. For 10 MHz, however, the $T$ is only 200 K.

Then TIU device is suitable for generating high frequency ultrasound because the height of frequency extends the limit of the power concentration in terms of temperature.

In addition to the thermal factor, electromigration is also to be considered, which depends on the electrode material.

### 3.2 Attenuation of high frequency ultrasound

In terms of enhancing the acoustic power and the efficiency, driving at high frequency is suitable to TIU device as we described above. But one problem we should consider is the attenuation of airborne ultrasound. It is known that sound attenuation length (the length with which the sound attenuates by 6dB) becomes short in proportion to $1/\omega^2$ in a frequency range lower than 1 MHz. But fortunately at a higher frequency than 1 MHz, the attenuation length does not decrease dramatically. The attenuation lengths at 2 MHz and 10 MHz are 8 mm and 1.5 mm, respectively, from the experimental data in **Fig. 3**.

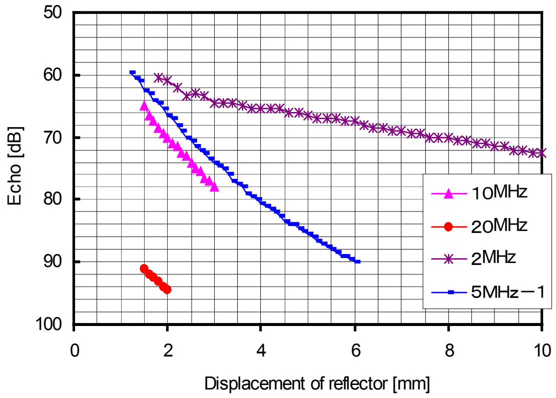



**Fig. 3:** Attenuation of airborne ultrasonic echo versus displacement of the reflector.

### 3.3 Wavelength and impedance matching

Until this section, we assumed emitted sound was plane wave. But as for applications in relatively low frequency sound emission in which the sound wavelength is larger than the emitter size, attaching a horn over the emitter as is shown in **Fig. 4** enhances the acoustic power. The figure (a) is the equivalent circuit of TIU emission. The load impedance $Z$ ($Z= \rho_A v$ for plane wave) is the acoustic impedance of the air in front of the device. The $Z_T$ is the equivalent internal impedance of the thermal emission written as

$$Z_T = \rho_A v \beta , \tag{11}$$

$$\beta = v\sqrt{\frac{C_A}{j\omega\alpha_A\gamma}} \quad . \tag{12}$$

For example, the $\beta$ is about 85 at 100 kHz. Then if we solve this impedance mismatching using a horn as is shown in **Fig. 4** (b), we can improve the output. In the following experiments, however, we evaluate the emission without such a horn.

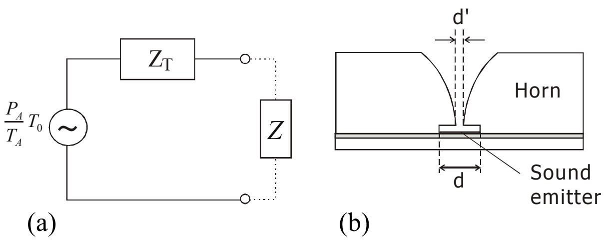



**Fig. 4:** (a): Equivalent circuit of TIU emission. (b): A method to extract acoustic power.

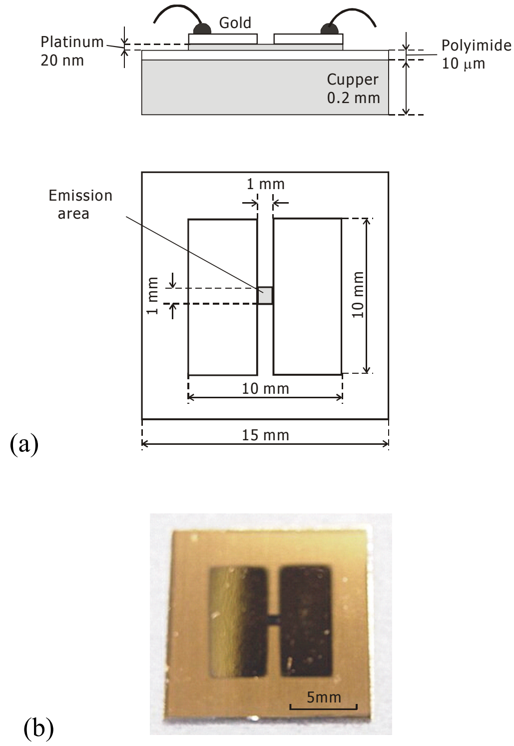



**Fig. 5:** (a): Structure of experimental device. Electrical power is concentrated on the 1-mm-square emission area. (b): Photograph of the experimental device.

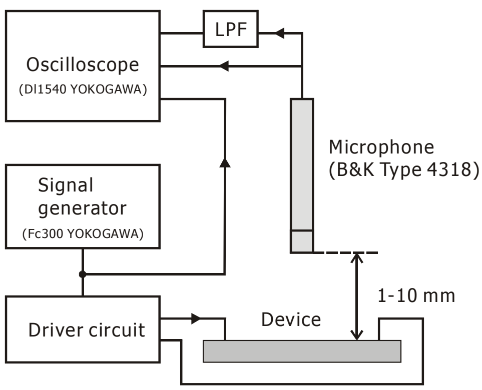



**Fig. 6:** Experimental setup. We observed emitted sound with a microphone (B&K type 4318) of bandwidth 100 kHz.

## 4. Basic experiments

In these experiments, we used platinum (20 nm thick) for the top conductive film. The thermal insulator was realized with polymide (10 $\mu$m thick, RIKACOAT SN-20 New Japan Chemical Co., Ltd) coated on a cupper plate as the bottom heat conductive base. This device is easy to be fabricated in laboratory, and the term $\alpha C$ in Eq. (3) is comparable to that of porous silicon. The resistance of the top conductive film was 4 [Ω].

Before examining high frequency and high intensity ultrasonic emission, we confirmed the basic property of the device. The experimental setup is shown in **Fig. 6**.

When we gave input signal shown in **Fig. 7**, the microphone located at 10 mm from the device surface observed a waveform as shown in the figure. Though the input signal was a rectangular pulse with 10-$\mu$s width, the observed signal was deformed because the bandwidth of the microphone was 100 kHz. We confirmed, however, the device emitted 10-Pa sound for 1 [W/mm$^2$] input.

Next we applied high power pulse with 1 [$\mu$s] pulse-width to the 1 [mm$^2$] emitter. Though we could not measure the actual peak of the sound pressure (as it is beyond the microphone's bandwidth), we plotted the peak value of the observed signal for various input power. The results are shown in **Fig. 8**. When we gave the pulse train at 10 kHz, we could increase the momentary input power up to 1 kW without having breakdown. The input power was calculated from the input current waveform. The 1 kW input power corresponds to 10 kPa ultrasound theoretically.

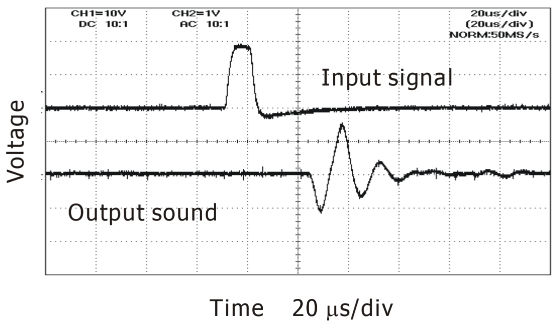



**Fig. 7:** Observed acoustic pressure for a rectangular pulse with a 10 [$\mu$s] pulse-width.

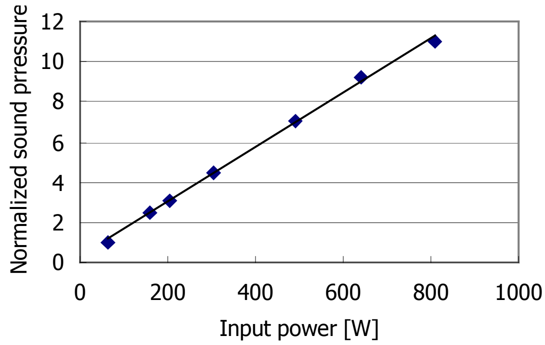



**Fig. 8:** Observed sound pressure versus input electrical power for 1 μs pulse train. Theoretically, 1 kW input causes 10 kP sound emission.

## 5. Experiments of radiation pressure

If acoustic wave with sound pressure $p$ reflects at a reflector, stationary pressure (radiation pressure)

$$P = G\frac{p^2}{\rho v^2} \tag{13}$$

is felt by the reflector. The $G$ is a constant related to the reflection property of the surface. If all the acoustic energy is absorbed on the surface, the $G$ is equal to 1. Meanwhile for the surface that reflects all the sound energy, the $G$ is 2.

Observed radiation pressure is shown in **Fig. 9**. We gave a signal as shown in the figure (a). Pulses with 1 μs pulse-width were generated at 10 kHz for 20 ms with 125 ms interval. The upper waveform in **Fig. 9** is a microphone's signal after low-pass-filtering with 100 Hz cut off. The momentary input power was 1 kW that was calculated by the input current. The microphone was located at 1 mm from the surface.

Theoretically the effective value of the emitted sound power during the 20 ms of the driving term, was 1,000 Pa. On the other hand, the average radiation pressure of 0.1 Pa means the effective value of sound pressure at the microphone was 100 Pa. Though we have not resolved this disaccord, we confirmed the device could generate more than 1 kPa ultrasound momentarily, and apply significant radiation pressure.

In the next experiment, we tried to hold a small object by the radiation pressure. As shown in Fig. 10, we put a small film of 20 μg over the device. When we applied the same signal as the above experiment (1 $\mu$s pulse at 10 kHz with 1 kW peak power) to the device, we observed movement of the object. The total force of 0.1 Pa radiation pressure over 1 $mm^2$ is 10 $\mu$gf. We could confirm an intense sound generation also in this experiment.

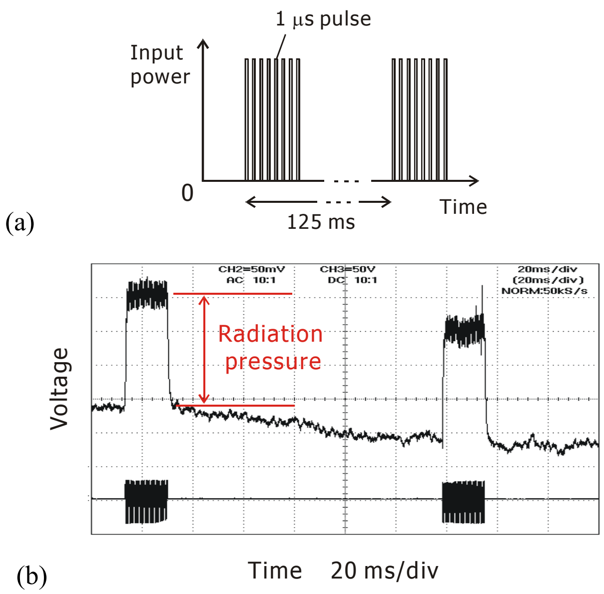



**Fig. 9:** (a): Driving signal. (b): The upper waveform is a microphone's signal after low-pass filtering. For the upper waveform, 3 divisions implies 0.1 Pa. The lower waveform is a microphone's signal without low-pass filtering. Output voltage of 1 V corresponds to 0.67 Pa.

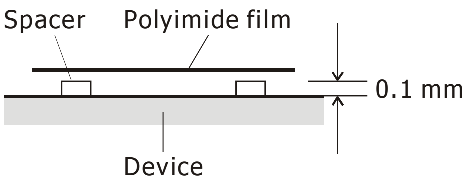



**Fig. 10:** Experiment of non-contact manipulation. We confirmed the movement of the film by the same signal as that in Fig. 9 (1 $\mu$s pulse at 10 kHz with 1 kW peak power).

## 5. Summary

In this paper we discussed methods to obtain intense ultrasound from TIU (Thermally Induced Ultrasound) device for applications using non-linear effects of ultrasound.

The essence of the improvement was concentrating the input power both spatially and temporally. And driving at high frequency was effective to reduce the temperature rise of the device.

Applying this theory to a practical device, we observed more than 1,000 Pa ultrasonic intensity, and succeeded in holding a small object (1 mm square, 20 $\mu$g) by the radiation pressure.

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