

A PARAMETRIC ARRAY PMUT LOUDSPEAKER WITH HIGH EFFICIENCY AND WIDE FLAT BANDWIDTH

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ABSTRACT

A previous study demonstrated that a piezoelectric micromachined ultrasonic transducer (PMUT) could be used to construct a PA loudspeaker, and developed a prototype. In this paper, we describe the performance of a PA loudspeaker fabricated using a more developed package. Our PA loudspeaker consists of an array of PMUTs with two resonance frequencies and uses an ‘out-of-phase’ driving technique, resulting in high power efficiency (up to 71%) and a wide flat radiation bandwidth. We also describe the characteristics of the PA sound, which depend on the method used to modulate the audible signal.

KEYWORDS

piezoelectric transducer; parametric array loudspeaker; PMUT; broadband transducer; ultrasonic transducer;

INTRODUCTION

A parametric array (PA) loudspeaker can radiate highly directional audible sound via the PA phenomenon based on the nonlinear characteristics of the propagation of finite amplitude acoustic beams [1]. In 1975, Bennett and Blackstock reported the first experimental study of a PA in air [2]. In 1983, Yoneyama et al. first attempted to make a PA loudspeaker [1], although commercial PA loudspeakers were not produced until 1998, because it was too difficult to generate an audible sound. In general, PA loudspeakers consume much more power than conventional loudspeakers [3], because a PA loudspeaker generates audible sounds indirectly, via so-called ‘second order nonlinear’ effects, and large-amplitude ultrasonic sound must be generated to realize the PA phenomenon. In addition, the sound radiation efficiency is very low in air, even at ultrasonic frequencies, due to the impedance mismatch between air and a conventional acoustic radiator. Therefore, a conventional acoustic radiator in air uses its resonance frequency for operation to maximize the power efficiency; the typical radiation bandwidth of a conventional PA loudspeaker is usually much narrower than that of audible sound. To date, many studies that have sought to improve PA loudspeakers have focused on signal-processing techniques and driving circuitry to compensate for its drawbacks [4, 5].

Recently, we adopted a more basic approach to improve the performance of PA loudspeakers, aiming for a better radiating transducer based on a piezoelectric micromachined ultrasonic transducer (PMUT) array [6]. Previous studies showed that micro-machined ultrasonic transducers (MUTs) have a small characteristic mechanical impedance with a thin

flexible radiating plate [7, 8]. This can increase electroacoustic efficiency by up to 80%; in addition, the quality factor of a thin flexible radiating plate is low, which can increase the power bandwidth of the radiation frequency by half. Consequently, in a PA loudspeaker based on a PMUT array, the power efficiency and radiation bandwidth can be improved dramatically by adopting an appropriately designed PMUT array.

Here, we describe the design and fabrication of a PA loudspeaker based on a PMUT array using three techniques. We also report that the PA sound depends on the method used to modulate the music signal.

DESIGN AND FABRICATION

We overcame the problems of conventional PA loudspeakers, i.e., the low power efficiency and narrow frequency bandwidth, by selecting a PMUT array of the appropriate thickness and using a new driving technique for double-resonance radiators [6].

Lumped parameter model

The mechanical impedance of a PMUT can be reduced by using a thin radiating plate [7, 8]. To design a PMUT for application to a PA loudspeaker, a lumped parameter model was used to predict the efficiency and frequency bandwidth, as shown in Fig. 1 [6]. Here, we briefly describe a lumped parameter model of a flexural-mode transducer.

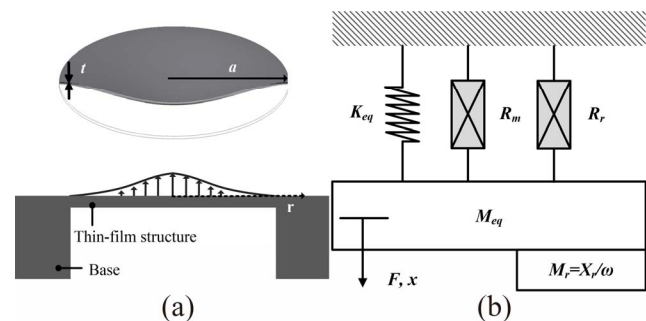


Figure 1: Thin film transducer, (a) structure and mode shape, (b) lumped parameter model with a single degree of freedom.

Figure 1(b) shows a single degree of freedom lumped parameter model of a thin film PMUT transducer. It includes parameters such as the equivalent mechanical mass, M_{eq} , the stiffness of the radiation plate, K_{eq} , and equivalent resistance, R_m . Using this model, the mechano-acoustic efficiency, η_{MA} , and a quality factor, Q , can be expressed in the frequency

region around resonance using the following equations:

$$\eta_{MA} = R_r / (R_m + R_r) = Q_m / (Q_m + Q_r) \quad (1)$$

$$Q = 1 / (1/Q_m + 1/Q_r) \quad (2)$$

The frequency bandwidth of a PMUT is inversely proportional to the quality factor, Q. Therefore, the design goal for a PMUT for use in a PA loudspeaker is to increase the mechano-acoustic efficiency and decrease the quality factor. Fig. 2 shows that a thin film transducer radiator can have a mechano-acoustic efficiency of up to 80% in air and a quality factor as low as 50 if it is less than 15 μm thick [6].

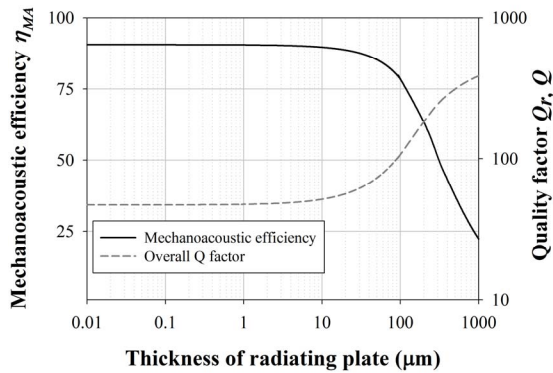


Figure 2: Relationship between the membrane thickness, t , and the mechano-acoustic efficiency and quality factor.

Dual transducer array with out-of-phase driving

The radiation frequency bandwidth is important for a PA loudspeaker, because the audible sound frequency bandwidth is 20 kHz. However, in a flexural-mode transducer using a PA loudspeaker, the bandwidth around the resonance frequency might be at most 4 kHz because of the minimum quality factor [6]. Therefore, to extend the radiation frequency bandwidth, we used two unit transducers with different resonance frequencies ($f_1 = 100$ kHz, $f_2 = 109$ kHz).

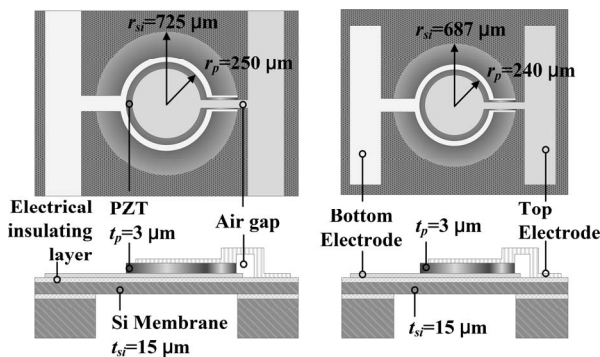


Figure 3: Structure and dimensions of the two unit drivers.

The dimensions of the two unit transducers are shown in Fig. 3 [6]. Fig. 4 shows the frequency response curve of the

pressure using a dual resonance transducer array. The frequency is normalized to 100 kHz and the amplitudes of the velocity are normalized to the peak value. Since the frequencies are between the two resonances, the two unit drivers vibrate out-of-phase. This phenomenon causes a deep null, shown by the black line in Fig. 5. Therefore, we introduced a new method called 'out-of-phase driving' (OPD) [6]. Using this driving technique, the f_2 unit driver drives an out-of-phase signal. Then, the two unit drivers vibrate in-phase between the two resonances shown in Fig. 4 and the deep null disappears, as shown by the gray line in Fig. 5

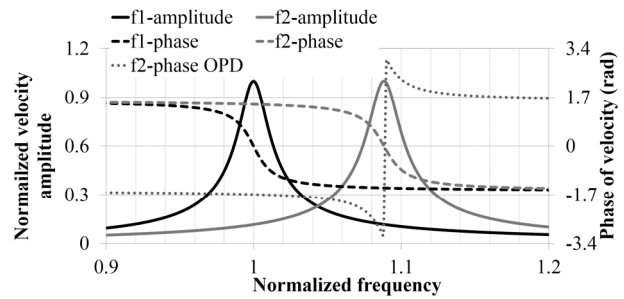


Figure 4: Calculated frequency response curve of the dual transducer array, normalized to the amplitude and phase velocity.

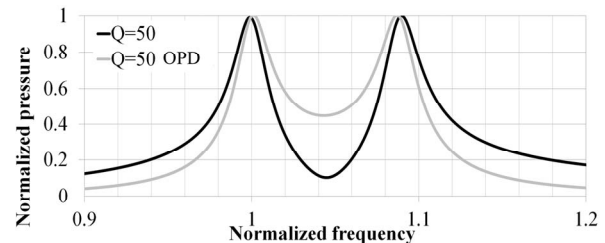


Figure 5: Calculated frequency response curve of the dual transducer array, normalized using the amplitude of pressure.

Array design

The unit drivers are placed to obtain the appropriate radiation area and a mix of the two types is used to obtain a nonlinear interaction.

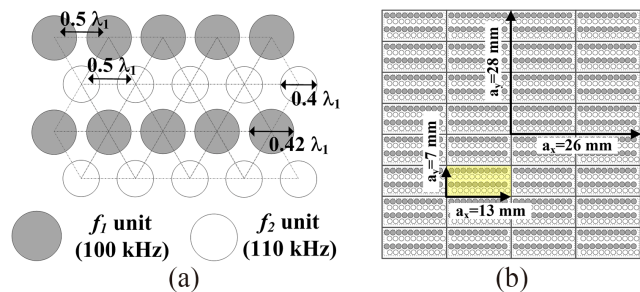


Figure 6: PA loudspeaker subarray design showing (a) the arrangement of the drivers and (b) the overall array dimensions.

The units are aligned using a triangular design, to place as many units in the same area as possible. For the subarray shown in Fig. 6 (a), the size and number of unit drivers in the subarray were determined after considering the uniformity of the fabrication process [6]. The subarray consisted of 14 f1 units and 14 f2 unit and measured 13 mm long by 7 mm wide. In this study, the PA loudspeaker transducer consisted of 32 subarrays, as shown in Fig. 6(b).

PACKAGING

In a recent study, a prototype PA loudspeaker was packaged using the front structure of the PMUT as a radiation plate [6], as shown in Fig. 7(a).

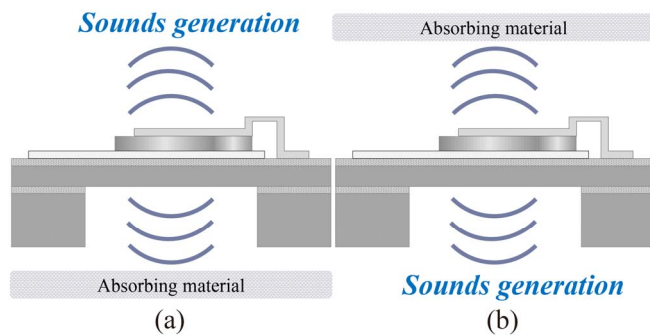


Figure 7: The position of the radiation plate of the PA loudspeaker seen from the (a) front and (b) back.

However, with this packaging method, the PMUT structure is damaged easily if the surface of the PA loudspeaker is touched. Therefore, it might not be a suitable packaging method for use with a PA loudspeaker. In addition, the input signal lines are exposed (see Fig. 8(a)), so this packaging method has limited use in an actual speaker.

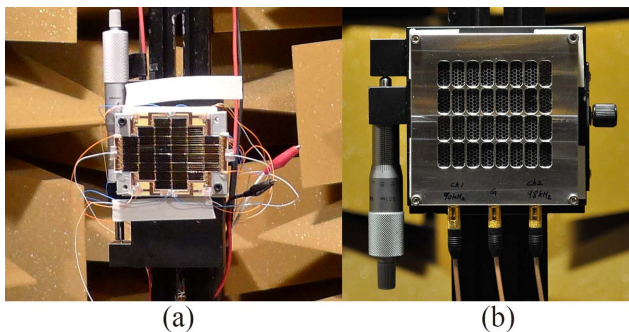


Figure 8: PA loudspeaker packaging method: (a) prototype and (b) new packaging method.

To overcome this, we devised a new packaging method that makes it easier to handle the speaker (see Fig. 9) and to simplify the configuration of the visible signal lines. The improved packaging method is shown in Figs. 8(b) and 9. As Fig. 8 shows, only three signal lines are visible and the back of the PMUT looks like the radiation plate in Fig. 7(b). The surface of the speaker forms a grid frame, and touching it will

not damage the speaker, making it easier to handle, as shown in Fig. 9.

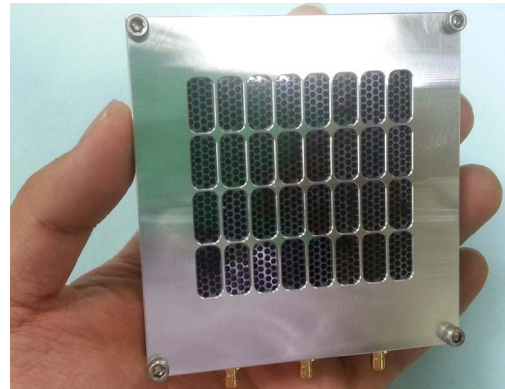


Figure 9: PA loudspeakers made using the new packaging method.

RESULT AND DISCUSSION

Acoustic efficiency

Table 1 shows the performance data for the f1 and f2 units with an applied DC bias voltage of 15 V.

Table 1: Measured data for the PMUT units.

Performance	f ₁ unit	f ₂ unit
Resonance frequency (kHz)	91.3	102.1
Admittance in air (μS)	112	-
Admittance in a vacuum (μS)	444	-
Quality factor in air	43.2	42.8
Quality factor in a vacuum	170	177
Electro-acoustic efficiency	67.2	71.0

The peak conductance of the f1 unit was 112 μS in air and 444 μS in a vacuum. Consequently, the measured electro-acoustic efficiency was ~70%, which is close to the theoretical maximum of up to 80%. The resonance frequency was 90.7 kHz in air and 91.3 kHz in a vacuum, and the quality factor was 43.2 in air and 170 in a vacuum. This result shows that the PMUT has high electro-acoustic efficiency and a low quality factor in air (i.e., a wide frequency bandwidth) compared with standard ultrasonic transducers.

Frequency response of primary frequency

The acoustic characteristics of the fabricated PA loudspeaker were measured in a semi-anechoic room (3 m × 3 m × 2 m). The input signals used for each channel were produced by a function generator (Agilent 33522A) and the sound pressure generated by the PA loudspeaker was measured through a reference microphone (B&K 1/8-inch microphone, Type 4138). The results are shown in Fig. 10.

In-phase (IPD) and out-of-phase (OPD) driving were used. With OPD, the null between the two resonances disappeared and the SPL level increased in the high-frequency region. The flat region of the frequency response was extended to 12.3 kHz (±3 dB bandwidth).

Frequency response of the difference frequency

Figure 11 shows the measured SPL of the difference frequency wave (DFW). The frequency response for IPD dropped rapidly at 7 kHz, while this drop disappeared for OPD. The DFW signal bandwidth was 12 kHz (± 3 dB bandwidth).

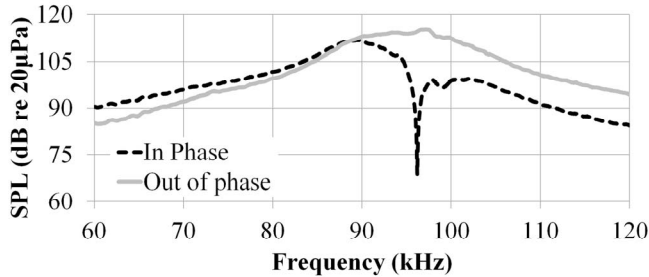


Figure 10: Measured SPL of a PA loudspeaker (distance 1 m, input voltage $1 V_{pk}$, 15 V DC bias).

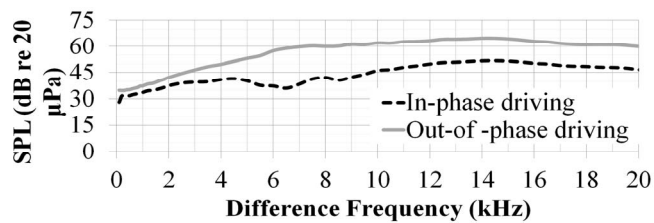


Figure 11: Measured SPL of the DFW (distance 1 m, input voltage $2 V_{peak-to-peak}$, 15 V DC bias).

Modulation of audible sound

Previously, the input signal was used to measure the characteristics of the DFW, simply by summing the carrier frequencies (90 kHz) for audible sound. However, for a PA loudspeaker used as a speaker, a modulation method is used with audible sound, with carrier frequencies as an input signal. Therefore, we examined the dependence of the DFW on the two modulation methods, as shown in Fig. 12.

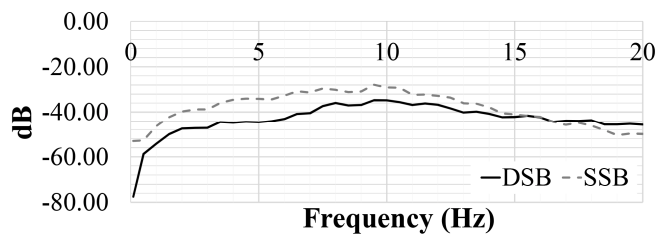


Figure 12: Measured DFW (modulation method: DSB, SSB).

This confirmed that the single side band (SSB) modulation method performed better than the double side band (DSB) modulation method. Future work should analyze this result in more detail.

CONCLUSION

We designed, fabricated, packaged, and measured a PA

loudspeaker consisting of PMUTs. The measured mechano-acoustic efficiency was up to 70% and a wide frequency bandwidth of 12.3 kHz was obtained using two resonance units and OPD. We also devised a new packaging method that makes it easier to handle the loudspeaker. We demonstrated the high performance of the SSB modulation method for audible sound with carrier frequencies as the input signal. There is now the potential to realize a PA loudspeaker with dramatically reduced power consumption and wide frequency bandwidth, with potential use in portable devices.

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REFERENCES

- [1] M. Yoneyama, J.-ichiroh Fujimoto, Y. Kawamo, and S. Sasabe, "The audio spotlight: An application of nonlinear interaction of sound waves to a new type of loudspeaker design," *J. Acoust. Soc. Am.* 73, 1532–1536, (1983).
- [2] M. B. Bennett and D. T. Blackstock, "Parametric array in air," *J. Acoust. Soc. Am.* 57, 562–568 (1975).
- [3] America Technology Corporation, "Theory, History, and the Advancement of Parametric Loudspeakers," (2003).
- [4] F. J. Pompei, "The use of airborne ultrasonics for generating audible sound beams," *J. Audio Eng. Soc.* 47 (9), 726–731 (1999).
- [5] E. L. Tan, P. Ji and W. S. Gan, "On preprocessing techniques for bandlimited parametric loudspeakers," *Applied Acoustics.* 71 (5), 486-492 (2010).
- [6] Yub Je, Haksue Lee, Kyoungun Been and Wonkyu Moon, "A micromachined efficient parametric array loudspeaker with a wide radiation frequency band", *J. Acoust. Soc. Am.* Accepted (2015)
- [7] Y. Je, H. S. Lee, and W. K. Moon, "The impact of micromachined ultrasonic radiators on the efficiency of transducers in air," *Ultrasonics.* 53 (6), 1124-1134 (2013).
- [8] I. O. Wygant, M. Kupnik, J. C. Windsor, W. M. Wright, M. S. Wochner, G. G. Yaralioglu, M. F. Hamilton and B. T. Khuri-Yakub, "50 kHz capacitive micromachined ultrasonic transducers for generation of highly directional sound with parametric arrays," *IEEE Trans. Ultra., Ferro. Freq. Cont.* 56 (1), 193-203 (2009).

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