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PMUTs array with dynamic directivity: A study of its underwater acoustic power intensity

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Abstract—**This paper presents the design and fabrication process of a PMUT array with adaptive directivity in order to study the beam pattern and acoustic power intensity of PMUT arrays. The proposed PMUT array consists of four 6×6, 8×8, 12×12, and a directional 6×6 arrays. Each array can be actuated separately. A detailed mathematical study, which is followed by FEM simulation, on directivity , beam pattern, and the acoustic power intensity is discussed. The fabricated array has resonance frequency of 160 kHz underwater with 4 levels of directivity. The measurement results are compared with the analytical and simulation results.**

Index Terms—**PMUT, beam pattern, omnidirectional, acoustic power intensity**

I. INTRODUCTION

The low attenuation of ultrasound signals in water, oil, human body, etc. makes it a promising alternative to electromagnetic wave communication. Therefore, ultrasound is commonly used in many applications and different environments; from in-body medical imaging to in-air range finding and underwater acoustic sensor network (UASN) applications [1], [2]. Among different ultrasound transducer technologies, piezoelectric micromachined ultrasound transducer (PMUTs) are a promising alternative to conventional ones. PMUTs benefit from small size, ease of fabrication, low power consumption, low cost, and tunable design parameters for a wide range of applications.

Depending on the targeted working environment, ultrasound transducers should be implemented and operated differently to optimize them for a specific application. For example, in a narrow underwater channel or for in-body imaging applications, it is desired to pursue a directional ultrasound beam pattern to prevent reflections and to increase the imaging resolution, respectively. For localization and communication of sensor nodes in UASN applications, it is however necessary to have an omnidirectional ultrasound beam pattern. Otherwise, point-to-point communication between some nodes may be lost. Besides the directivity, acoustic power intensity is of equal importance to the design of an ultrasound transducer. The acoustic power intensity defines the distance range the ultrasound wave can travel. For all applications, it is typically attempted to maximize the output acoustic power intensity of a transducer, which leads an increased Signal to Noise Ratio (SNR). A transducer can be made directional by (i) using a parabolic acoustic reflector [3] and (ii) using an array of transducers. The first way of making a transducer directional can increase the output power intensity at the point of interest. However, somewhat counterintuitive, the output acoustic power intensity cannot be increased by using a directional array of transducers. The reason is explained in Section II.

In this paper, a PMUT array with variable directivity for underwater applications is designed and fabricated. The PMUT array is intended to make point-to-point communication in the distance range of 1-2 meters with four levels of directivity, from omnidirectional to very directional. Furthermore, the directivity equations and design rationale are discussed. The relationship between the directivity of a PMUT array to its output acoustic power intensity is also presented. All theoretical considerations are compared with FEM simulations and measurements on the fabricated PMUT array.

II. THEORETICAL ANALYSIS AND ARRAY DESIGN

A. Analysis of the directivity and acoustic power intensity

The beam pattern of a PMUT array depends on different parameters, such as the layout of the array elements, the beam pattern of each PMUT element, and the distance between each PMUT. In this work it is assumed that each PMUT element has an ideal omnidirectional beam pattern. A 1D or linear array along the x-axis, results in a beam pattern which is symmetrical in the y-axis. Accordingly, the beam pattern of a 2D array is symmetrical in both x and y axis. For the sake of simplicity, all mathematical analysis was done for a 1D array, but eventually can be extended to a 2D array. The directivity of an array of PMUTs is defined by (1) [4].

$$D = 2\pi / \int_{4\pi} H^2(\theta) d\Omega \tag{1}$$

where, $H(\theta)$ is the beam pattern of the array respect to the elevation angle (θ). The integration is done in a hemispherical space, since in real application, the transducer is rigidly baffled, which reflects the ultrasound wave and doubles the power intensity. By substituting the equation of a linear array beam pattern in (1) and calculating the integral in cylindrical

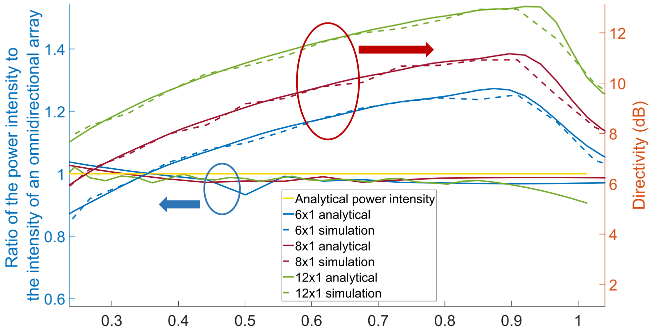

Fig. 1. The analytical calculation and FEM simulation of the power intensity ratio of a linear array with respect to an omnidiretional one with equal input actuation power; and the directivity of three 6×1, 8×1, and 12×1 linear arrays.

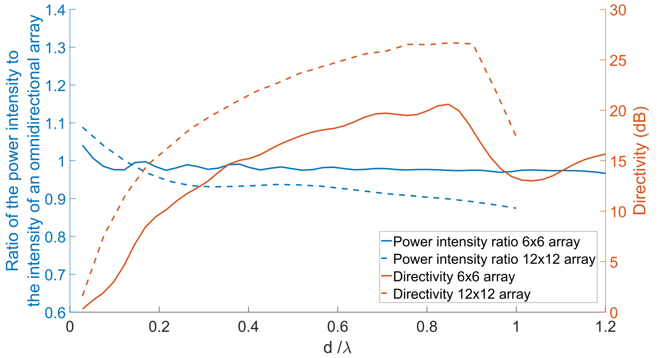

Fig. 2. The FEM simulation of the directivity and the axial acoustic power intensity ratio of 6×6 and 12×12 arrays with respect to an identical array with ideal omnidirectional directivity.

coordinates, the directivity of a linear PMUT array can be expressed as:

$$D_a = 2\pi / \left(2 \int_0^{\pi/2} \left[\frac{1}{N} \frac{\sin\left[(N/2)\right] kd \sin\theta}{\sin\left[(1/2)\right] kd\sin\theta} \right]^2 2\pi \cos\theta d\theta \right) \tag{2}$$

where N is the number of PMUT elements in the array, k is the wave-number and is equal to $2\pi/\lambda$, and d is the distance between each element. Fig. 1 shows the analytical calculation and FEM simulation using COMSOL Multiphysics 5.3a of the directivity of a linear array with 6, 8, and 12 PMUT elements with respect to the ratio of d to the wavelength (λ). The array is omnidirectional if the elements are placed close to each other. Furthermore, the specific value of d, at which the directivity is maximized, is always less than the wavelength, but converges to the wavelength by increasing the number of elements in the array.

To investigate the relationship between the directivity of an array and the axial output acoustic power intensity, the power intensity ratio of two different arrays was investigated as follows:

$$\frac{I_D}{I_O} = \frac{I_{avgD}}{I_{avgO}} \frac{D_D}{D_O} = \frac{P_D/2\pi r^2}{P_O/2\pi r^2} \frac{D_D}{D_O} \tag{3}$$

where I is the acoustic power intensity, I_{avg} is the average power intensity, and P is the acoustic power. I_{avg} is defined as the total radiated acoustic power divided by the area of a hemisphere with the radius of r, which surrounds the array. It should be noted that the D and O subscripts refer to the directional and omnidirectional array, respectively. The acoustic power for a linear transducer is equal to:

$$P_{total} = \frac{1}{2} \frac{1}{\rho_0 c_0} \int_{2\pi} p^2(r,\theta) r^2 d\Omega \tag{4}$$

in which, ρ_0 is the density of the medium (water in our case), c_0 is the speed of sound in the medium (around 1500 m/s in water), and r is the radial distance from the center point of the transducer. In (4) p is the pressure generated by the transducer in the targeted medium. For a linear array, the generated time-dependent pressure at coordinates (r, θ) can be calculated as following:

$$p(r,\theta,t) = N(\frac{A}{r}) \mathrm{e}^{j(\omega t - kr)} H(\theta) \tag{5}$$

where, A is a constant defined by the pressure generated by each individual element in the array. By substituting (5) in to (4), one can rewrite (3) as:

$$\frac{I_D}{I_O} = \frac{N_D^2}{N_O^2} \frac{H_D}{H_O} \frac{D_D}{D_O} \tag{6}$$

Using $H(\theta)$ and D_a from (1) and (2), (6) was found to be dependent to only the square ratio of the number of elements in the array, therefore:.

$$\frac{I_D}{I_O} = \left(\frac{N_D}{N_O} \right)^2 \tag{7}$$

From the theoretical derivations, (1) to (7), several conclusions can be drawn:

1) Equation (7) shows that by making an array directional, e.g. by increasing the distance between elements (d), the axial acoustic power intensity is not affected. This means that a directional array does not gain anything in the transmission distance range compared to an omnidirectional. It should be noted that in both directional and omnidirectional arrays, the input power is the same. In Fig. 1, the FEM simulation and analytical calculation both confirm that by making an array directional, the axial acoustic power intensity remains constant, and ideally equal to one.
2) The conclusion from (7) can also be understood from (5). It shows that the axial pressure of an array, regardless to its beam pattern and directivity, is always constant and equal to $N(\frac{A}{r})$. This is true if the number of elements in the array is kept constant.
3) It can be concluded from (2) to (5) that the integral of the beam pattern of a very directional array, is a small value. This means that the total radiated acoustic power

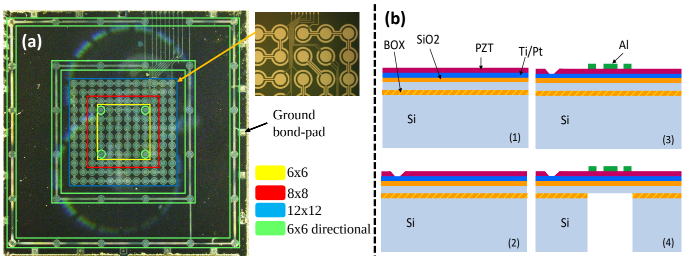

Fig. 3. (a) The fabricated PMUT array. The inset shows the magnification of few PMUTs from the central 12 × 12 array. (b) The fabrication process of the PMUT array.

is much smaller than the total input power to the array, and therefore the axial power intensity is constant.

A similar analysis, as Fig. 1, was performed on several 2D arrays. Fig. 2 shows the FEM simulation of the directivity and the axial acoustic power intensity ratio of 6×6 and 12×12 arrays with respect to an identical array with ideal omnidirectional directivity.

B. *PMUT array design*

As shown in Fig. 3, a highly dense 12×12 PMUT array at the center of a directional 6×6 array was designed. Each PMUT in the arrays has 410 μm diameter. The central dense array has a small inter-element distance ($d = 490\mu m$ and $d/\lambda = 0.052$), which results to an omnidirectional beam pattern. In order to vary the directivity of the dense array, it was divided in to 3 sub-arrays; a 6×6, 8×8, and 12×12; which can be actuated separately through different bond pads. The directional 6×6 array has a large value of the inter-element distance ($d = 2450\mu m$ and $d/\lambda = 0.26$). The directional 6×6 array has 4 shared elements with the dense 12×12 central array. These 4 elements are also accessible by separate bond-pads. Each individual PMUT consists of a 6 μm silicon membrane and a 1 μm PZT layer. The PMUTs have a resonance frequency of 160 kHz underwater; this results in a wavelength of around 9 mm.

III. FABRICATION AND MEASUREMENT

The PMUT array was fabricated based on an SOI wafer, by forming the 410 μm diameter membrane using a Deep Reactive Ion Etching (DRIE) process. First, a 1 μm PZT layer was deposited on SiO_2(600 nm)/Ti(20 nm)/Pt(250 nm) by a sol-gel process [5]. Then, the 200 nm aluminum layer as the top electrode was deposited and patterned. Finally, the 6 μm thick Si membrane was formed by a DRIE process and the 2 μm buried oxide layer (BOX) was removed in Buffered HF (BHF). The fabrication process is shown in Fig. 3(b).

The fabricated PMUT array was wire bonded to a PCB and, as shown in Fig. 4, the PCB was placed underwater and connected to the controlling board by cable. The controlling board can select different arrays on the die to operate. A 1 mm needle hydrophone (Precision Acoustics Ltd.) was used to record the acoustic signal. The PMUT array was connected to a stepper motor that allows us to measure the beam pattern with 0.9° resolution.

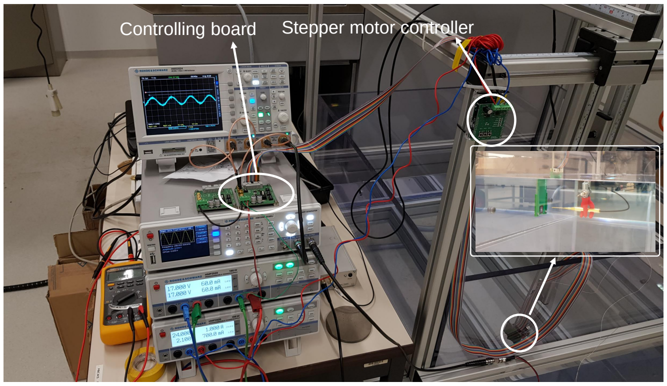

Fig. 4. The measurement setup to characterize the fabricated PMUT array underwater. The top-right inset shows the wire bonded array to the PCB.

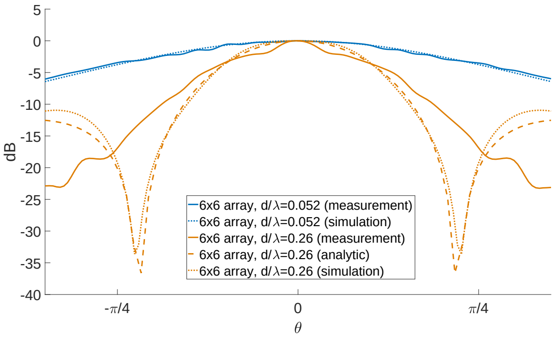

Fig. 5. The FEM simulation, analytical calculation, and measurement result of the beam pattern of two directional and omnidirectional 6 × 6 arrays.

IV. RESULTS AND DISCUSSION

The beam pattern of each PMUT array is measured under water by a 1 mm needle hydrophone. Fig. 5 shows the beam pattern of the omnidirectional and directional 6×6 arrays with $d/\lambda = 0.052$ and $d/\lambda = 0.26$, respectively. The result is compared with the FEM simulation results and analytical results obtained from (2).

In order to investigate the output acoustic power intensity of arrays, their normalized received signal along several distance intervals (1-10 cm) were compared to each other. If a directional array has a higher power intensity compared to an omnidirectional one, the received normalized signal along the distance should be attenuated less than the signal received from the omnidirectional array. As shown in Fig. 6, the attenuation is approximately the same for all arrays, which means that the axial acoustic power intensity is not changing by making an array more directional. The time domain response of each array to a burst sinewave with 10 cycles is shown in Fig. 7. As expected, no significant amplitude difference between a directional and omnidirectional 6×6 array was observed. However, the directional 6×6 array results in a smaller

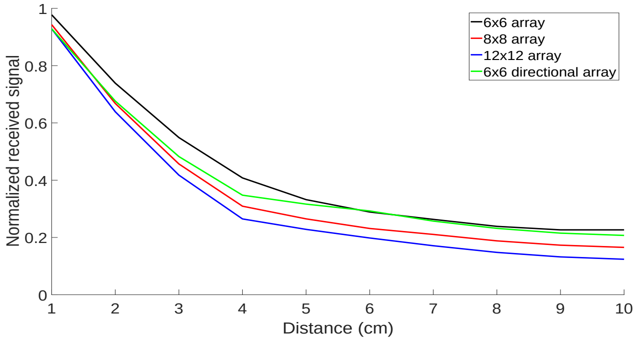

Fig. 6. Investigating the axial power intensity by comparing the normalized measured signal along a distance range of 1-10 cm to the measured signal at 1 cm.

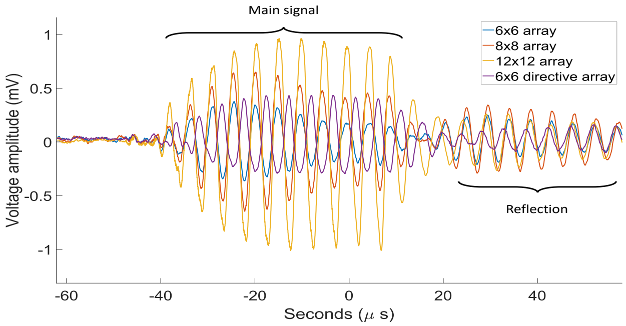

Fig. 7. The time response of all arrays respect to a burst sinus signal with 10 cycles. The received reflection is also illustrated in the figure.

reflected signal, since less ultrasound waves impact the surface of the water.

In this work some mathematical approximations were made to simplify the calculations. In this way, the differences between FEM simulations and analytical results in Figs. 1 and 2 can be explained. The approximations were as following:

Firstly, it was assumed that the beam pattern of a linear array is not dependent to the azimuth angle. This is true when all elements are in phase and the beam pattern of each element is omnidirectional. However, the azimuth angle should be considered in a 2D array. Fig. 8(a) and (b) shows the simulated beam pattern of two 2D circular and square arrays with a total of 49 elements. As shown, the layout of a circular array is more symmetrical in azimuthal direction, which results in a better symmetrical beam pattern. In order to make the beam pattern even more uniform, the outer elements in the array should be placed closer together to reduce the number of lobes in the azimuthal direction, as shown in Fig. 8(c). In other words, the beam pattern is less directional in azimuthal direction. However, it is easier to perform beam steering in a square array rather than circular array.

Secondly, In the calculation of (2), it was assumed that r is the same for all elements. This is a good approximation only when the radial dimension of the array is small enough compared to r. Otherwise, when the transducer is large, e.g. a directional array with large value of d ($d > \frac{2}{N}\sqrt{\frac{r\lambda}{\pi}}$), the

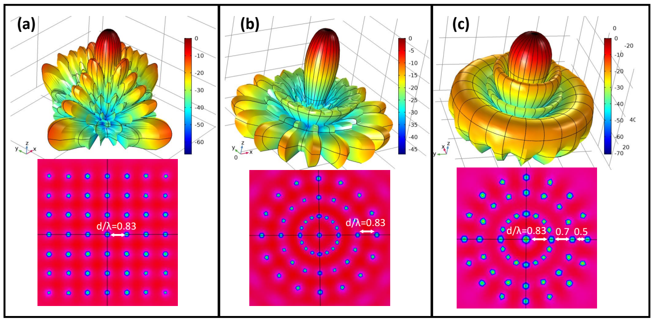

Fig. 8. The beam pattern of a (a) square, (b) circular, (c) and a second circular array with 49 elements. The layout of each array with the value of d is also shown.

difference between the distance of the point of interest in space and each element in the array is not negligible. This explains why in Figs. 1 and 2, when making the 12×12 array more directional, the power intensity ratio declined faster than in the other arrays.

Thirdly, In a linear array, the integral of the beam pattern was always calculated in cylindrical coordinates. However, this is not true when the array is very dense and the beam pattern is omnidirectional. In this case, the beam pattern is in a spherical space rather than a cylindrical; as a result, the term $\cos\theta d\theta$ in (2) should be replaced by $\sin\theta d\theta$.

V. CONCLUSION

A PMUT array with adaptive directivity has been fabricated. The array consists of four nested 6×6, 8×8, 12×12, and a directional 6×6 arrays. Each array can be actuated separately. A detailed study on the directivity, beam pattern, and the acoustic power intensity of PMUT arrays has been presented. It was shown that by making an array directional, the axial acoustic power intensity remains constant. Furthermore, the axial generated pressure by an array can only be increased by either adding the input power or by increasing the number of elements. Finally, all simulation and analytical results have been proven by measuring the fabricated PMUT array.

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