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Experimental Investigation of the Effect of Subdicing on an Ultrasound Matrix Transducer

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***Abstract*—Over the past decades, real-time three-dimensional (3D) medical ultrasound has attracted much attention since it enables clinicians to diagnose more accurately. This calls for ultrasound matrix transducers with a large number of elements, which can be interfaced with an application-specific integrated circuit (ASIC) for data reduction. An important aspect of the design of such a transducer is the geometry of each element, since it affects the mode of vibration and, consequently, the efficiency of the transducer. In this paper, we experimentally investigate the effect of subdicing on a piezoelectric (PZT) transducer. We fabricate and acoustically characterize a prototype PZT matrix transducer built on top of ASICs. The prototype transducer contains subdiced and non-subdiced elements, whose performance can be directly compared under the same conditions. Measurement results show that subdiced elements have a better performance compared to non-subdiced ones. Subdicing increases the peak pressure by 25%, raises the bandwidth by 10% and reduces the ringing time by 25%.**

Keywords—matrix, ultrasound transducer, PZT, ASIC, subdicing.

I. Introduction

Medical ultrasound is an indispensable imaging modality due to its flexibility and non-invasive character [1]. Over the past decades, real-time three-dimensional (3D) ultrasound has attracted much attention since it enables clinicians to diagnose more accurately than with conventional two-dimensional (2D) ultrasound imaging [2]. A common way to generate real-time 3D images is by using a matrix transducer that contains many elements (in the order of thousands) of very small pitch (in the order of hundreds of micrometers). It is a great challenge to build a matrix array with such a vast number of elements because it requires thousands of electrical connections between the matrix array and the imaging system, which is impractical if not impossible. One of the approaches to overcome this issue is by manufacturing the transducer matrix directly on top of an application-specific integrated circuit (ASIC) to reduce the number of cables [3]–[5].

Most of the clinically available ultrasound probes are made of a piezoelectric material (PZT). The performance of a PZT transducer is directly related to its geometry, which affects the mode of vibration of the elements [6], [7]. If the width-to-thickness ratio of the element is smaller than 0.7, the element will mainly vibrate in the thickness mode, which is more efficient due to the piston-like motion. If the width-to-thickness ratio is greater than 0.7, unwanted vibration modes will reduce the efficiency of the transducer. Since the wavelength in PZT is about twice the wavelength in water (λ), we can say that thickness vibration is obtained when the width of the element is well below 0.7λ [5]–[9]. Thus, elements with a small width are preferred to achieve high efficiency. On the other hand, to radiate more power into the medium, the element should be as large as possible. This leads to a contradiction that can be solved by subdicing, which means cutting each transducer element into smaller sub-elements with non-through cuts [7].

The influence of subdicing on a matrix transducer integrated with an ASIC has been previously investigated through simulations in [5]. In this paper, we investigate the effect of subdicing experimentally. For this purpose, we build a prototype PZT matrix (on top of ASICs) having subdiced and non-subdiced elements, so they can be directly compared. We analyze the transmit performance of all individual elements in the time and frequency domain, and we also compare the directivity pattern of subdiced and non-subdiced elements.

II. Methods

A. Prototype matrix transducer

We have fabricated a prototype PZT matrix transducer that operates at 7.5 MHz and consists of 48×80 elements with a pitch of 300 µm × 150 µm (1.5λ × 0.75λ). Along the 300 µm pitch direction, the matrix alternates between subdiced, yielding sub-elements of 150 µm × 150 µm, and non-subdiced elements every 6 rows, as shown in Fig. 1. In this way, it is possible to directly compare subdiced with non-subdiced elements under the same conditions. The PZT matrix was mounted on top of 4×1 tiled ASICs whose element-level circuits match the pitch of the array. The prototype transducer interfaces with a Verasonics V1 imaging system (Verasonics, Inc., Kirkland, WA, USA) using a custom-designed motherboard PCB [3], [10]. The

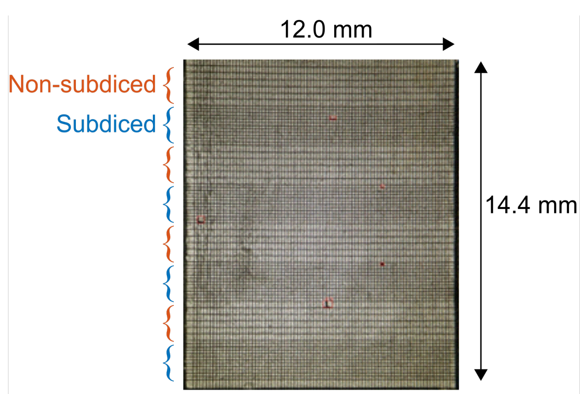

Fig. 1. A photograph of the fabrication of the PZT matrix with subdiced and non-subdiced rows.

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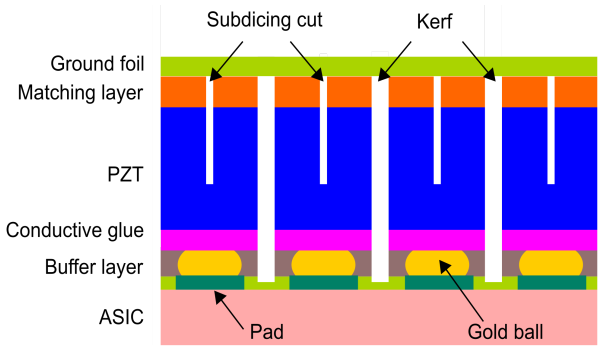

Fig. 2. Acoustic stack of the prototype matrix transducer (subdiced elements).

geometry and the composition of the acoustic stack are shown in Fig. 2. For subdiced elements, one single cut was applied with a cutting depth of 70% of the total element thickness, i.e., the thickness of the PZT and the matching layer. According to [7], a cutting depth of 70% is sufficient to reduce spurious vibration modes while providing mechanical stability to the elements.

B. Transmit characterization

The transmit characterization was performed with a 1 mm calibrated needle hydrophone (SN 2082, Precision Acoustics Ltd., Dorchester, UK) placed at 100 mm away from the transducer surface. The Verasonics V1 was used to drive each array element individually with a 30 V unipolar pulse. The hydrophone signals were amplified by a 60 dB amplifier (AU-1519, Miteq, Inc., Hauppauge, NY, USA), digitized by an oscilloscope (DSO-X 4024A, Agilent Technologies, Santa Clara, CA, USA), and transferred to a computer automatically.

To evaluate the directivity pattern of the elements, a 0.2 mm calibrated needle hydrophone (SN 1688, Precision Acoustics Ltd., Dorchester, UK) was placed at 50 mm away from the transducer surface and rotated from 0 to 60 degrees. Before measuring the directivity of each evaluated element, the hydrophone was aligned by finding the maximum acoustic pressure.

III. Results and Discussion

In Fig. 3(a), the time domain responses, plotted in solid lines, of a non-subdiced and a subdiced element are shown. The envelope of the pulse is plotted in dotted lines. The measured peak pressure (i.e., envelope peak) of this subdiced element is about 1.5 times higher than for the non-subdiced one. Another parameter obtained from the time response is the ringing time Δt_{-20dB}, defined as the time interval for the envelope amplitude to decrease below -20 dB of its corresponding peak. The ringing time of the subdiced element is about 0.8 µs. For the non-subdiced element, this is about 1.32 µs.

The frequency domain responses of the subdiced and non-subdiced elements are depicted in Fig. 3(b). The non-subdiced element shows an unwanted dip at around 7 MHz, reducing its -6 dB bandwidth (BW_{-6dB}). For the subdiced element, the unwanted dip is shifted to higher frequencies, yielding a higher bandwidth. This indicates that subdicing reduces spurious vibration modes, as expected.

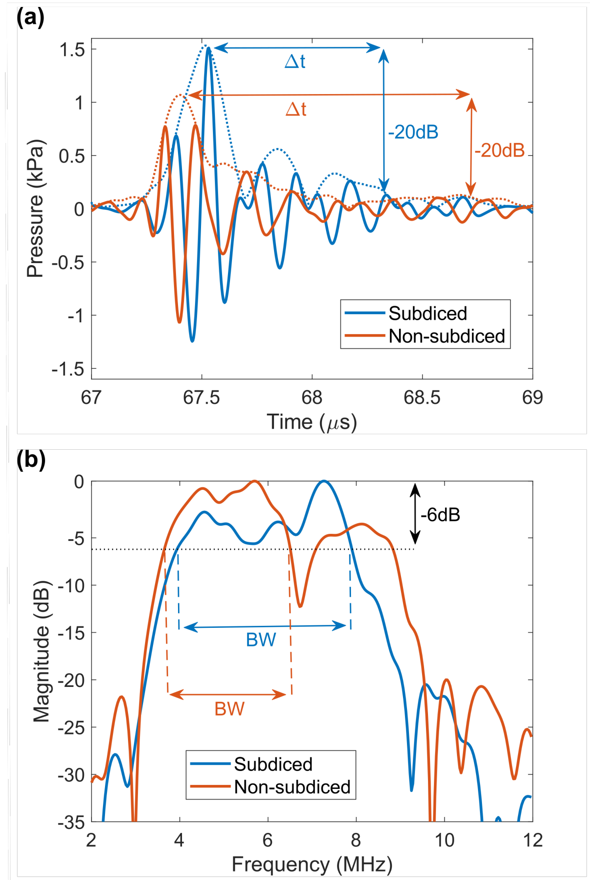

Fig. 3. Time (a) and frequency (b) domain responses of a non-subdiced and a subdiced element.

The relative peak pressure across all elements of the matrix is shown in Fig. 4. It is visible that the subdiced rows are, in general, more efficient than the non-subdiced ones. As seen, the majority of the array elements are functioning, but some elements are defective. Rows 2 and 48 do not transmit possibly due to defective (or missing) bond wires. The remaining defective elements were likely damaged during the fabrication process.

The directivity pattern of a subdiced and a non-subdiced

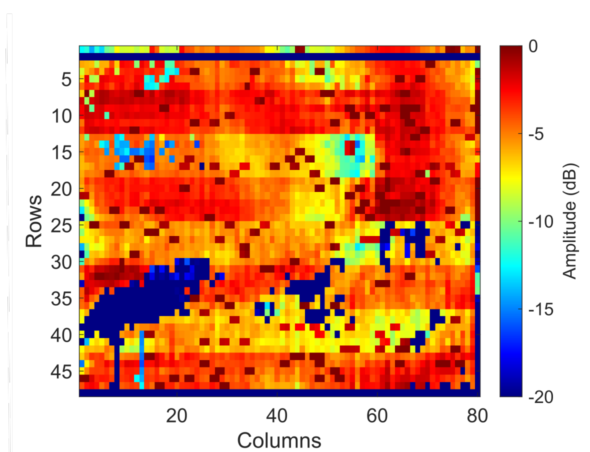

Fig. 4. Relative peak pressure of all transducer elements (corrected for the hydrophone directivity).

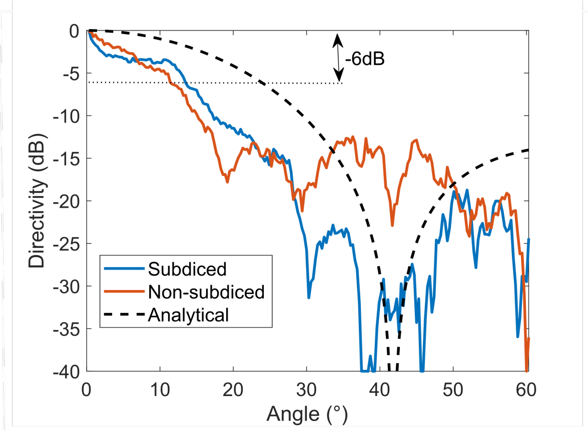

Fig. 5. Directivity pattern of a non-subdiced and a subdiced element.

element is shown in Fig. 5. The analytical curve of an ideal piston in a rigid planar baffle is also plotted for comparison [11]. The beam width of the prototype matrix (for both subdiced and non-subdiced elements) is considerably narrower than the ideal one. For the non-subdiced element, extra peaks occur at around 40 degrees, where a dip is expected. The cause of these peaks has not yet been identified as this is not observed in simulations [4], [7]. The directivity pattern of the subdiced element agrees better with the analytical curve.

The overall performance of the prototype transducer matrix is summarized in Table I. The listed values represent the average over 1920 array elements. An exception to this is the value of the beam width, which was obtained by averaging the results over 12 elements. The measured peak pressure of subdiced elements is 25% higher than the non-subdiced ones. This confirms that subdicing increases the transmit efficiency even though the surface area of the element is reduced. Besides, subdiced elements have a shorter pulse duration with a ringing time that is 25% smaller. The peak frequency of subdiced elements was raised by 1 MHz and the bandwidth by 10% when compared to non-subdiced elements.

TABLE I. COMPARISON BETWEEN NON-SUBDICED AND SUBDICED ELEMENTS

Parameter	Non-subdiced	Subdiced
Peak pressure (kPa)	1.2 ± 0.2	1.5 ± 0.4
Ringing $_{\Delta t\text{-}20dB}$ (μs)	1.4 ± 0.1	1.1 ± 0.3
Peak frequency (MHz)	5.2 ± 0.2	6.1 ± 0.2
Bandwidth $_{-6dB}$ (%)	32 ± 4	42 ± 9
Beam width $_{-6dB}$ (°)	22.0 ± 2	29.0 ± 2

IV. Conclusions

In this paper, the performance of a prototype matrix transducer built on ASICs and consisting of subdiced and non-subdiced elements was analyzed in transmit. On average, subdicing increases the peak pressure by 25%, raises the bandwidth by 10%, and reduces the ringing time by 25%. In addition, the directivity pattern of subdiced elements is more similar to the analytical curve. The results indicate that subdicing improves the performance of the transducer with large elements (width-to-thickness ratio larger than 0.7).

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