An Integrated Ring CMUT Array for Endoscopic Ultrasound and Photoacoustic Imaging

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Abstract — This work presents our preliminary results on developing an integrated quad-ring CMUT array for endoscopic ultrasound and photoacoustic imaging. We have designed and fabricated a ring capacitive micromachined ultrasonic transducer (CMUT) array composed of 512 elements distributed among four concentric rings each having 128 elements. The operational frequency of each ring was chosen to achieve a similar pressure beam profile for all the rings. The device’s inner and outer diameters measure 5.0 and 10.1 mm, respectively. The CMUT array was integrated with custom front-end ICs using a quartz fan-out board. This bench-top assembly allowed connection to a single ring (i.e., 128 elements) at a time. Thus far, we have built assemblies with connections to the two outer rings. We have successfully demonstrated real-time volumetric imaging with these assemblies using nylon wire phantom and metal spring phantom.

Keywords – endoscopic; photoacoustic; ultrasound; real-time; forward-looking; volumetric imaging; capacitive micromachined ultrasonic transducer; CMUT

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I. INTRODUCTION

Ring arrays have many advantages in catheter-based and endoscopic ultrasound imaging applications where real-time volumetric imaging is desired. The sparse nature of a ring 2D array implies fewer elements than a fully populated 2D array of the same extent, potentially resulting in small number of required cables. The ring geometry provides a central lumen that can be utilized for a variety of other applications, such as introducing biopsy and therapeutic devices and optical fibers for photoacoustic imaging.

Capacitive micromachined ultrasonic transducer (CMUT) technology is particularly suited for atypical geometries, such as a ring array; fabrication complexity of a ring CMUT array is the same as those of regular rectangular CMUTs.

In this work, we are investigating the utility of an integrated forward-looking quad-ring CMUT array for endoscopic applications. This paper provides a brief overview of the fabricated CMUT array, the integrated assembly, our volumetric imaging platform, and preliminary characterization and imaging results.

II. METHODS

A. 512-element Quad-Ring CMUT Array

We designed and fabricated a 512-element ring CMUT array using our polysilicon sacrificial release process with through-wafer via interconnects [1]. The transducer array elements are arranged into four concentric rings #1-4 each consisting of 128 elements. They are placed on concentric circles with diameters of 6.0, 7.2, 8.5, and 9.7 mm for rings #1-4, respectively. All 128 transducer array elements within each ring are the same; however, they differ among the four rings in size and center frequency. The center frequencies are 16, 12, 8, and 6.5 MHz for rings #1-4, respectively. The device’s inner and outer diameters are 5.0 and 10.1 mm, respectively. The ring CMUT array specifications are summarized in Table I and an optical picture of the device is shown in Fig. 1.

The center frequencies for the four rings are chosen such that their acoustic pressure beam profiles are similar. As seen in Fig. 2, the continuous-wave (CW) pressure beam profile simulations (performed for each ring at its corresponding center frequency) show that the chosen frequencies indeed result in similar beam profiles. For these simulations, we assumed a continuous single-element ring piston transducer in place of each of the ring arrays. All the rings have a natural focus of

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Ring #1</th>
<th>Ring #2</th>
<th>Ring #3</th>
<th>Ring #4</th>
</tr>
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<tbody>
<tr>
<td>Number of elements</td>
<td>128</td>
<td>128</td>
<td>128</td>
<td>128</td>
</tr>
<tr>
<td>Center frequency (MHz)</td>
<td>16</td>
<td>12</td>
<td>8</td>
<td>6.5</td>
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<tr>
<td>Active aperture outer diameter (mm)</td>
<td>6.100</td>
<td>7.392</td>
<td>8.702</td>
<td>9.914</td>
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<td>Element width (µm)</td>
<td>100</td>
<td>152</td>
<td>170</td>
<td>186</td>
</tr>
<tr>
<td>Element height (µm)</td>
<td>136</td>
<td>152</td>
<td>214</td>
<td>234</td>
</tr>
<tr>
<td>CMUT cells per elements</td>
<td>12</td>
<td>16</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>CMUT cell plate radius (µm)</td>
<td>14</td>
<td>16</td>
<td>19</td>
<td>21</td>
</tr>
<tr>
<td>CMUT plate thickness (µm)</td>
<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
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<tr>
<td>Radius of top electrode (µm)</td>
<td>11</td>
<td>12.5</td>
<td>14.8</td>
<td>16.3</td>
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<tr>
<td>Vacuum gap height (µm)</td>
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<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>Insulator layer thickness (µm)</td>
<td>0.146</td>
<td>0.146</td>
<td>0.146</td>
<td>0.146</td>
</tr>
</tbody>
</table>
around 10 mm and provide a minimum imaging depth of at least 4 mm.

B. Integrated Assembly

Direct connection of small transducer array elements (e.g., those of this ring array) to a commercial imaging system would typically result in significant loss in SNR and hence degraded image quality [2-3].

The ring CMUT array is integrated with custom integrated circuits (ICs) in a pin-grid-array (PGA) package for bench-top testing (Fig. 3). The architecture of the ICs enables seamless connection to commercial imaging systems. The ICs provide a dedicated low-noise amplifier for each transducer array element and allow up to ±50 V external pulses to pass through to the transducer [2].

The CMUT arrays are fabricated with through electrical vias and hence electrical pads are located on the backside of the device for tight packaging. Therefore flip-chip bonding is used to access the transducer array elements. The array is flip-chip bonded to a custom quartz fan-out board that provides the connections between the CMUT and the ICs. The ICs are wire-bonded to the fan-out board. Due to the large number of elements in the array, each assembly is wire-bonded in such
way to enable imaging with one full ring at a time (i.e., 128 elements).

In this paper, we are reporting on the results of two assemblies built with connections to rings #3 and #4.

C. Volumetric Imaging Platform

For imaging, we use a 128-channel PC-based ultrasound data acquisition platform from Verasonics (Verasonics, Inc., Redmond, WA) with our in-house software.

Our GPU-based imaging software for a ring array uses synthetic phased-array beamforming; it employs Hadamard coding, Norton’s weightings, and cosine apodization to improve SNR, achieve full-disk-aperture resolution, and reduce side-lobe levels, respectively, for better image quality [4]. In addition to ultrasound imaging, our software is capable of photoacoustic imaging using receive-only dynamic focusing. In fact, it is capable of co-registered dual-modality ultrasound and photoacoustic imaging.

III. RESULTS

A. Characterization

We performed a variety of characterization experiments; among them are electrical input impedance measurement of the transducer array elements, hydrophone measurements, and pulse-echo response measurement of the integrated assembly. Due to brevity, we are only showing a single hydrophone measurement result here.

Fig. 4 shows the hydrophone transient signal and its corresponding frequency spectrum for an element of the ring #3 assembly. For this experiment, the hydrophone was placed at 2.4 mm distance, CMUT array was biased at 40 V, and a unipolar 25 V excitation pulse was used.

B. Imaging Results

We performed several ultrasound imaging experiments with both ring #3 and ring #4 assemblies using imaging phantoms.

IV. CONCLUSION AND FUTURE WORK

We have successfully demonstrated a fully integrated 512-element quad-ring CMUT array and its volumetric imaging capability using nylon wire and metal spring imaging phantoms and photoacoustic imaging experiments are imminent.

We plan to prepare and characterize more assemblies utilizing rings #1 and #2. Longer term plans include designing an appropriate fan-out board and interface box that would allow imaging with all four rings in a single assembly. Finally, we will package the device to integrate with an endoscope.
ACKNOWLEDGMENT

This work was funded by the National Institutes of Health under grant NHLBI R01-HL67647, USA. We would like to thank Texas Instruments (former National Semiconductor Corporation, Santa Clara, CA) for their valuable support in the design and fabrication of the IC. CMUT fabrication was done at the Stanford Nanofabrication Facility (Stanford, CA), a member of National Nanotechnology Infrastructure Network.

REFERENCES


Figure 5. Volume rendered Images of a metal spring acquired with ring #3 (left) and ring #4 (right) assemblies using one of our imaging software packages. Imaging depth is 45 mm.

Figure 6. Images of a custom wire phantom made of ten 0.15-mm diameter nylon fishing lines acquired with ring #3 (top) and ring #4 (bottom) assemblies. Left and middle panels show two orthogonal B-mode images. Right panel shows a constant-R image at 22.9 mm. Imaging depth is 25 mm.