Photoacoustic Imaging Using a Two-Dimensional CMUT Array

I. O. Wygant, X. Zhuang, P. S. Kuo, D. T. Yeh, O. Oralkan, B. T. Khuri-Yakub
Edward L. Ginzton Laboratory
Stanford University, Stanford, CA 94305
Email: iwygant@stanford.edu

Abstract— **Photoacoustic imaging is a promising complement to pulse-echo ultrasound imaging because it provides contrast between areas with different light absorption characteristics. Specifically, regions with higher blood concentration can be identified, which is useful for imaging vascularization and the early detection of cancer. Here we present volumetric photoacoustic images of a vessel-like phantom. The phantom consists of three 1.3-mm diameter tubes inside a tissue mimicking material. The center tube is filled with ink to provide optical contrast. A two-dimensional capacitive micromachined ultrasonic transducer (CMUT) array is used for acoustic detection. The use of a two-dimensional transducer array eliminates the drawbacks of a mechanically scanned system and enables volumetric imaging. CMUT technology enables new types of transducer arrays that would benefit photoacoustic imaging. Fully populated two-dimensional arrays, annular ring-arrays, and high-frequency arrays have all been demonstrated using CMUT technology and have advantages for photoacoustic imaging systems. Other advantages of CMUT technology for photoacoustic imaging include a wider bandwidth than comparable piezoelectric devices and ease of integration with electronics.**

Keywords-*photoacoustics, capacitive micromachined ultrasonic transducer, CMUT, three-dimensional, integrated electronics*

I. Introduction

In photoacoustic imaging, the optical absorption properties of a material are imaged by detecting the ultrasound emitted when the material is illuminated by a laser. The emitted ultrasound is due to the brief thermal expansions that occur when the laser's energy is absorbed by the material. Those regions that are more optically absorbent than others will generate a stronger acoustic signal. Thus, with an ultrasound transducer array or a mechanically scanned transducer, an image of the optical absorption properties of the material can be constructed. For medical imaging, photoacoustics is interesting because materials in the body have different optical absorption properties. A common motivation put forth for the development of photoacoustic imaging is the desire to image vascularization for the detection of cancerous tumors.

Laser pulse widths of around 10 ns and wavelengths between 600 nm and 1000 nm are typically used for photoacoustic imaging [1-4]. The wavelength is chosen to provide sufficient penetration and good optical contrast between the materials being imaged. The pulse length must be brief enough such that the volume expansions are short and efficiently generate ultrasound.

Photoacoustic imaging has been extensively studied. Impressive results have been published for the imaging of humans and small animals [1-4]. In this work, a capacitive micromachined ultrasonic transducer (CMUT) array is used to photoacoustically image a vessel-like phantom. Previous photoacoustic imaging work has typically relied on a single mechanically scanned piezoelectric transducer for detection of the laser-generated ultrasound. Using a CMUT array in place of a mechanically scanned element has a number of advantages. Large, two-dimensional arrays can be reliably fabricated using CMUT technology. A transducer array greatly speeds up the data acquisition time for a given aperture size. CMUT array geometries such as the ring array have also been demonstrated [5]. A ring array has the practical benefit that the laser light can come through the hole in the center of the array. Finally, CMUTs typically have wider bandwidth than comparable piezoelectric transducers. This is especially important given the broadband nature of the laser-generated ultrasound.

II. Experimental Setup

A diagram illustrating the setup is shown in Fig. 1. The CMUT array is located at the bottom of a 5 cm x 5 cm x 3 cm tank. Vegetable oil is used to couple ultrasound between the array and phantom. Vegetable oil is used because it is nonconducting and thus the array and electronics do not need to be insulated. The phantom consists of three 1.3-mm polyethylene tubes passing through a 2 cm x 2 cm x 3 cm block of tissue mimicking material (ATS Laboratories, Bridgeport, CT). The center tube is filled with black ink to provide optical contrast for the photoacoustic imaging.

The laser illuminates the phantom from the side. Ideally the laser should uniformly illuminate the material being imaged. Thus the laser beam is defocused to a $1/e^2$ diameter of approximately 6 mm. A ground glass diffuser in front of the tank further diffuses the laser light. The laser is a Q-switched, Nd:YAG laser with a 1.064 μm wavelength and 12-ns FWHM pulse duration. The energy of each laser pulse is 2.3 mJ. The laser was fired at a rate of 10 Hz. A photograph of the phantom and tank is shown in Fig. 2.

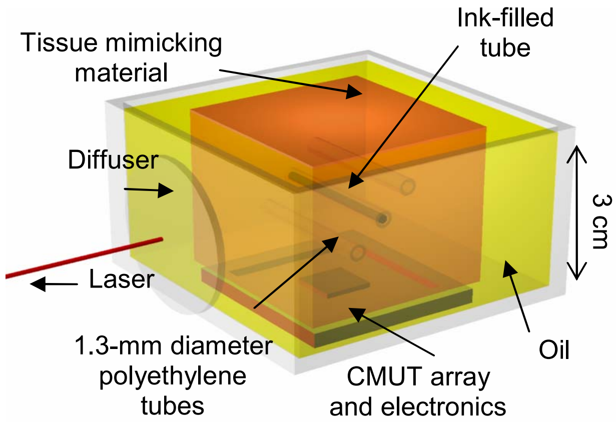

Figure 1. Vessel-like photoacoustic imaging phantom. Three 1.3-mm diameter tubes are inside a block of tissue mimicking material. The center tube is filled with ink to provide optical contrast. The phantom is illuminated by a laser from the side.

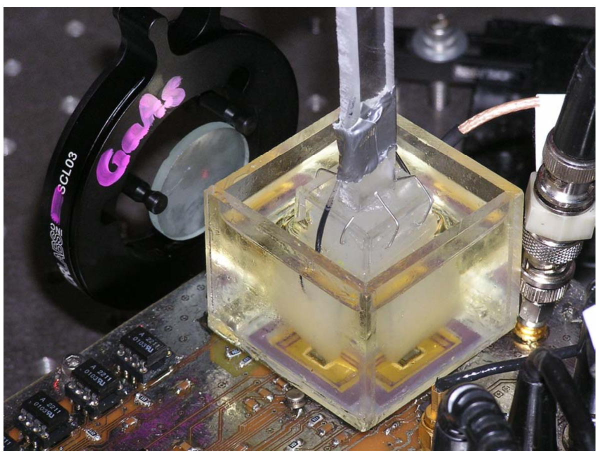

Figure 2. Photograph of the phantom and tank. The transducer array is located at the bottom of the tank. The diffuser at the left diffuses the laser beam to provide more uniform illumination of the sample.

III. CMUT ARRAY AND INTEGRATED ELECTRONICS

The transducer array has 256 elements (16 × 16 elements). Each element is 250 µm × 250 µm. Thus, the entire array size is 4 mm × 4 mm. The transducers have a center frequency of 5 MHz. The CMUT array was fabricated using a sacrificial silicon nitride process. A few of the key CMUT device parameters are shown in Table 1. A picture of the packaged device is shown in Fig. 3. The CMUT array and electronics are shown in Fig. 4. A more thorough description of the design and fabrication of the CMUT array is given in [6]. A description of the CMUT array and integrated electronics is given in [7].

The transducer array is flip-chip bonded to a custom-designed integrated circuit (IC) that comprises the front-end circuitry. The result is that each element is connected to its own amplifier via a 400-µm long interconnect. This means of integration mitigates the effect of parasitic cable capacitance and simplifies connecting the transducer array to an external system. The IC allows for the selection of a single element at a time. Thus 256 laser firings are required to acquire a single image with no averaging.

TABLE I. CMUT DEVICE PARAMETERS

Cell diameter, µm	36
Element pitch, µm	250
Number of cells per element	24
Membrane thickness, µm	0.6
Cavity thickness, µm	0.1
Insulating layer thickness, µm	0.15
Silicon substrate thickness, µm	400
Flip-chip bond pad diameter, µm	50
Through-wafer interconnect diameter, µm	20

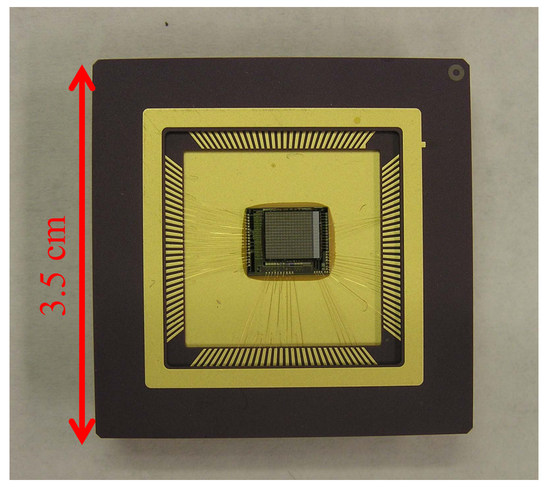

Figure 3. Package containing the transducer array and electronics.

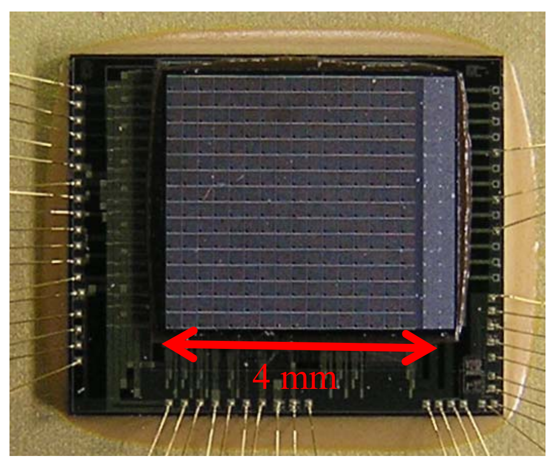

Figure 4. CMUT array flip-chip bonded to an integrated circuit that comprises the front-end circuitry for the array.

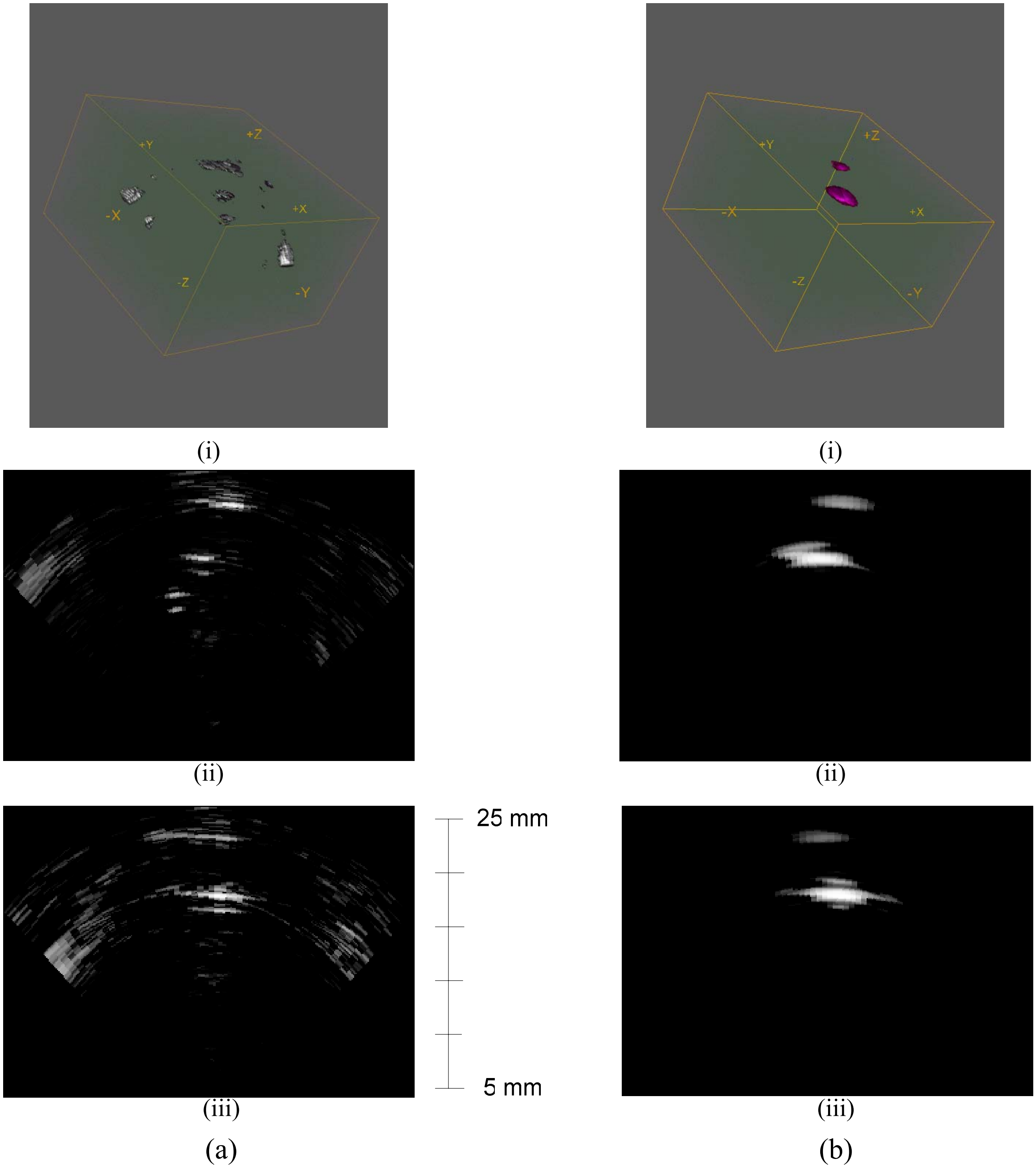

Figure 5. (a) Pulse-echo images of the phantom shown with 30-dB dynamic range. (b) Photoacoustic images shown with 20-dB dynamic range. The volume rendered image is shown in (i). XZ and YZ cross sections are shown in (ii) and (iii) respectively.

IV. RESULTS

Conventional pulse-echo imaging data and photoacoustic imaging data were acquired for the phantom. Photoacoustic data was acquired by recording an element's output after the laser excitation. The pulse-echo data was averaged 16 times to improve the signal-to-noise ratio. The photoacoustic data was averaged 4 times. Example pulse-echo and photoacoustic data acquisitions are shown in Fig. 6 and Fig. 7 respectively. The signal from the ink-filled tube can be identified in both figures. The individual element acquisitions are bandpass filtered and then used for image reconstruction. Both the photoacoustic image and pulse-echo image are constructed using a standard delay and sum image reconstruction algorithm.

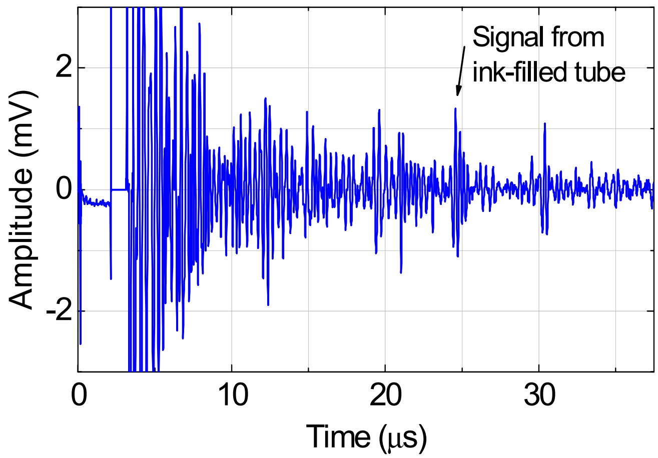

Figure 6. Example pulse-echo A-scan. Reflections from the three tubes can be identified.

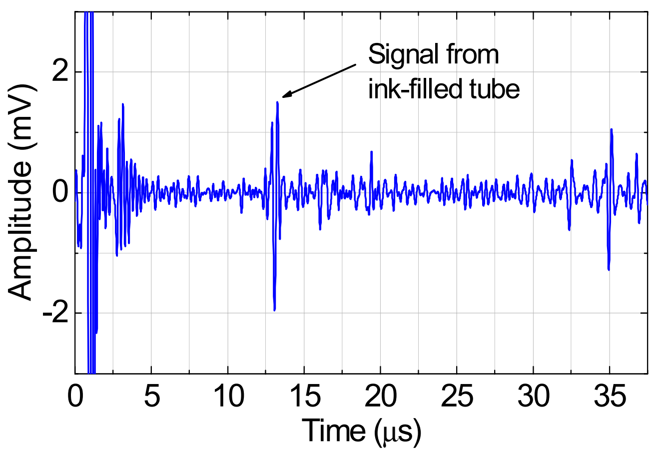

Figure 7. Photoacoustic data acquired for a single element. The signal from the ink-filled tube can be clearly seen. The signals seen in the first 5-μs are due to electronic noise of the laser and laser light incident on the transducer array.

Volume rendered and cross-sectional views of the pulse-echo and photoacoustic images are shown in Fig. 5. The three tubes are clearly seen in the pulse-echo image. The ink-filled tube is substantially brighter than the other tubes in the photoacoustic image.

V. CONCLUSION

Photoacoustic images obtained with a CMUT transducer array and integrated electronics are presented. These results demonstrate some of the advantages of CMUT technology for photoacoustic imaging. A transducer array such as the one used in this work has clear acquisition time advantages over a mechanically scanned system. By increasing the laser repetition rate, real-time images could be obtained with the system described here. Image resolution could be improved by using a larger aperture size. CMUT arrays as large as 128 × 128 elements have been fabricated [8]. The use of such large transducer arrays for photoacoustic imaging would provide both outstanding image quality and fast acquisition times.

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