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CMUT-based Volumetric Ultrasonic Imaging Array Design for Forward Looking ICE and IVUS Applications

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Abstract

Designing a mechanically flexible catheter based volumetric ultrasonic imaging device for intravascular and intracardiac imaging is challenging due to small transducer area and limited number of cables. With a few parallel channels, synthetic phased array processing is necessary to acquire data from a large number of transducer elements. This increases the data collection time and hence reduces frame rate and causes artifacts due to tissue-transducer motion. Some of these drawbacks can be resolved by different array designs offered by CMUT-on-CMOS approach. We recently implemented a 2.1-mm diameter single chip 10 MHz dual ring CMUT-on-CMOS array for forward looking ICE with 64-transmit and 56-receive elements along with associated electronics. These volumetric arrays have the small element size required by high operating frequencies and achieve sub mm resolution, but the system would be susceptible to motion artifacts. To enable real time imaging with high SNR, we designed novel arrays consisting of multiple defocused annular rings for transmit aperture and a single ring receive array. The annular transmit rings are utilized to act as a high power element by focusing to a virtual ring shaped line behind the aperture. In this case, image reconstruction is performed by only receive beamforming, reducing total required firing steps from 896 to 14 with a trade-off in image resolution. The SNR of system is improved more than 5 dB for the same frequency and frame rate as compared to the dual ring array, which can be utilized to achieve the same resolution by increasing the operating frequency.

Keywords

CMUT; intravascular ultrasound; intracardiac echocardiography; real time; volumetric imaging

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1. INTRODUCTION

High frequency catheter based ultrasonic devices are widely used in cardiovascular applications such as intravascular (IVUS) imaging and intracardiac echocardiography (ICE). Due to high image resolution requirement to resolve small structures in or around the heart vessels, operating frequency of these catheters should be on the order of 10–20 MHz. System design for these applications is extremely challenging since imaging catheters need to be as small as 1–3 mm in diameter hence the transducer area is very limited. Moreover, a central opening is generally required to enable for a guide wire or an interventional device. In addition, in order to provide forward-looking volumetric imaging, the transducer array needs to be a two dimensional array which results in excessive number of transmit and receive channels.

Since the small-sized, flexible catheter strictly limits the number of cables to connect it to the external processing unit, synthetic phased array processing is suitable. Therefore, the array channels must be multiplexed in multiple firing events to simplify the front end and reduce the cable count. This increases data collection time which reduces frame rate and causes artifacts due to tissue-transducer motion. In addition, these devices suffer from low signal-to-noise ratio (SNR) and poor contrast resolution due to small element size and single element firing in each pulse-echo operation. Single chip capacitive micromachined ultrasonic transducer (CMUT) with on-chip CMOS implementation provides great flexibility in designing array geometry and integrated front-end electronics, and can be used to address some of these challenges.

We have recently fabricated a single-chip forward-looking IVUS system design using monolithic CMUT-on-CMOS integration where dual ring CMUT arrays are fabricated directly on top of pre-processed CMOS wafers (Figure 1). In this study, to improve image SNR of the current imaging arrays and achieve high frame with low motion susceptibility, we propose a transmit array formed by a number of defocused annular rings that can emit a high intensity wave front through the imaging space. Thus, instead of using a single ring array in transmit we utilize the large unused area efficiently around the center guide wire opening and populate this area with annular ring arrays. By applying appropriate delays to each annular ring, a powerful single ring shaped line response can be generated. Since the same transmit aperture is used in each firing event, image reconstruction is performed by only receive beamforming which dramatically reduces total required firing steps.

2. METHODS

We have successfully implemented dual ring CMUT arrays for IVUS and ICE imaging applications. The former has 56 Tx and 48 Rx ring array elements in a 1.4-mm diameter silicon area operating at 20 MHz. The later operates at 10 MHz and has 64 Tx and 56 Rx array elements in a diameter of 2.1 mm (Figure 2). All transmit and receive circuitry have integrated on CMOS wafers underneath CMUT elements. Both systems require 13 external connections including digital control signals, 4-channel output, supply and bias voltages. CMOS electronics are manufactured using TSMC's 0.35-μm CMOS process on 8-inch silicon wafer reticle (Figure 3). All IC's in single-chip system are custom design which includes pulsers, capable of generating 25-V unipolar pulses and low-noise receiver trans-impedance amplifiers (TIAs) for each of the CMUT receive array elements. We have demonstrated the characterization and imaging performance of these devices in various studies [1–4]. In this study, ICE configuration (2.1-mm diameter array) is considered as a test case to explore the available design space offered by the CMUT-on-CMOS approach.

The dual ring CMUT-on-CMOS device with 4 output channels requires 896 firings to collect all transmit-receive combinations for image reconstruction. Considering an image depth of 40 mm, RF data collection takes around 50 ms without averaging and hence the image rate can be 20 frames per second. This frame rate is sufficient for real time volumetric imaging with single-chip device. However, since synthetic phased array technique is utilized for image reconstruction, motion artifact due to undesired tissue-transducer motion is a significant concern. To reduce motion susceptibility and capture real time images from moving high speed structures inside the heart, the number of firings should be reduced by at least 1/10th [5]. This could be achieved by using a transmit array formed by a number of defocused annular rings that can emit a high intensity wave front through the imaging space. Thus, instead of using a single ring array in transmit we can utilize the large unused area efficiently around the center guide wire opening and populate this area with annular ring arrays. By applying appropriate delays to each annular ring and focusing to a virtual ring shaped line behind the aperture, a powerful spherical wave front can be generated. Since the same transmit aperture is used in each firing event, image reconstruction is performed by only receive beamforming which dramatically reduces total required firing steps. In addition, using defocused annular rings in transmit also eliminates most of the front-end electronics related to transmit circuitry. The schematic description of dual ring CMUT array (2.1-mm device) and the annular ring transmit array configuration is shown in Figure 4.

The image SNR of a single pixel reconstructed using synthetic phased array can be calculated by:

$$SNR=20\log_{10}\left(\sqrt{N_T N_R}\right)+SNR_0 \quad (1)$$

where N_T is the number of transmit elements, N_R is the number of receive elements, and SNR_0 is the SNR of the pulse echo obtained by single transmit-receive pair [6]. Using multiple defocused elements in transmit improves transmitted beam intensity on the order of $\sqrt{K}$ where K is the number of defocused elements [7, 8]. Although, instead of using multiple elements in transmit a group of annular ring arrays are used in the proposed design, the SNR improvement can be calculated similarly considering active membrane area used in transmit. Consequently, the proposed transmit architecture improves the SNR of current system theoretically more than 5 dB. In addition to SNR improvement, since only a 56-element ring array is used in image reconstruction, the frame rate increases by 64 times. This increase, in imaging speed, results in extremely low motion susceptibility.

3. RESULTS

To test angular response of the proposed transmit array, we generated the simulated 1-way beam patterns of the defocused annular rings. In simulations, we used a 10 MHz Gaussian pulse with 50% fractional bandwidth. The attenuation and diffraction losses were ignored in these calculations. For comparison, we also simulated the beam patterns of a single transmit element in the dual ring array and non-focused response of the annular rings which are excited simultaneously. The simulation results are presented in Figure 5. The beam patterns are plotted at an axial depth of 13 mm and a 90° sector angle. As expected, single element beam pattern has a spherical angular response where the non-focused beam pattern has a narrower angular beam. On the other hand, the defocused annular ring produces beam patterns nearly the same angular response with the single element response. In addition, the maximum intensity calculated in the simulated defocused beam pattern is 15 dB greater than the maximum intensity of the single element beam pattern. These results show that defocused annular arrays have a wide viewing angle with high SNR.

We also reconstructed the 2-D point spread functions (PSFs) of the proposed design and our current dual ring array. The PSFs shown in Figure 6 were generated in $r\theta$ plane (B-scan) and $\theta\phi$ surface (C-scan). The B-scan PSFs were produced in a 90° sector for the on-axis point targets at 4 mm, 6 mm, 8 mm and 10 mm. Each PSF was log compressed 40-dB dynamic range. The beam widths along axial direction are identical in both designs. However, the arms of the PSF in defocused annular arrays are significantly longer when compared to the PSF of dual ring array as expected.

The only disadvantage of the proposed system is poor lateral resolution since image reconstruction is performed by only receive array and the resulting effective aperture is nearly halved with respect to the dual ring array. To achieve same image resolution from the new design operating frequency can be doubled. This results in a degradation of 16 dB in SNR due to the ultrasound attenuation in blood which has an attenuation coefficient of 0.2 dB/(MHz·cm) [9]. To compensate the SNR loss, signal averaging can be performed up to 64 times maintaining the frame rate at 20 fps with low motion susceptibility. Quantitative comparison of both array configurations can be seen in Table I.

4. CONCLUSIONS

In this study a new transmit array configuration for catheter based cardiovascular imaging applications is presented. The proposed design shows significant improvement in image SNR and increases frame rate. Low motion susceptibility and data collection period enables real time volumetric imaging of high speed heart valves. The proposed arrays are being fabricated and further imaging experiments will be performed.

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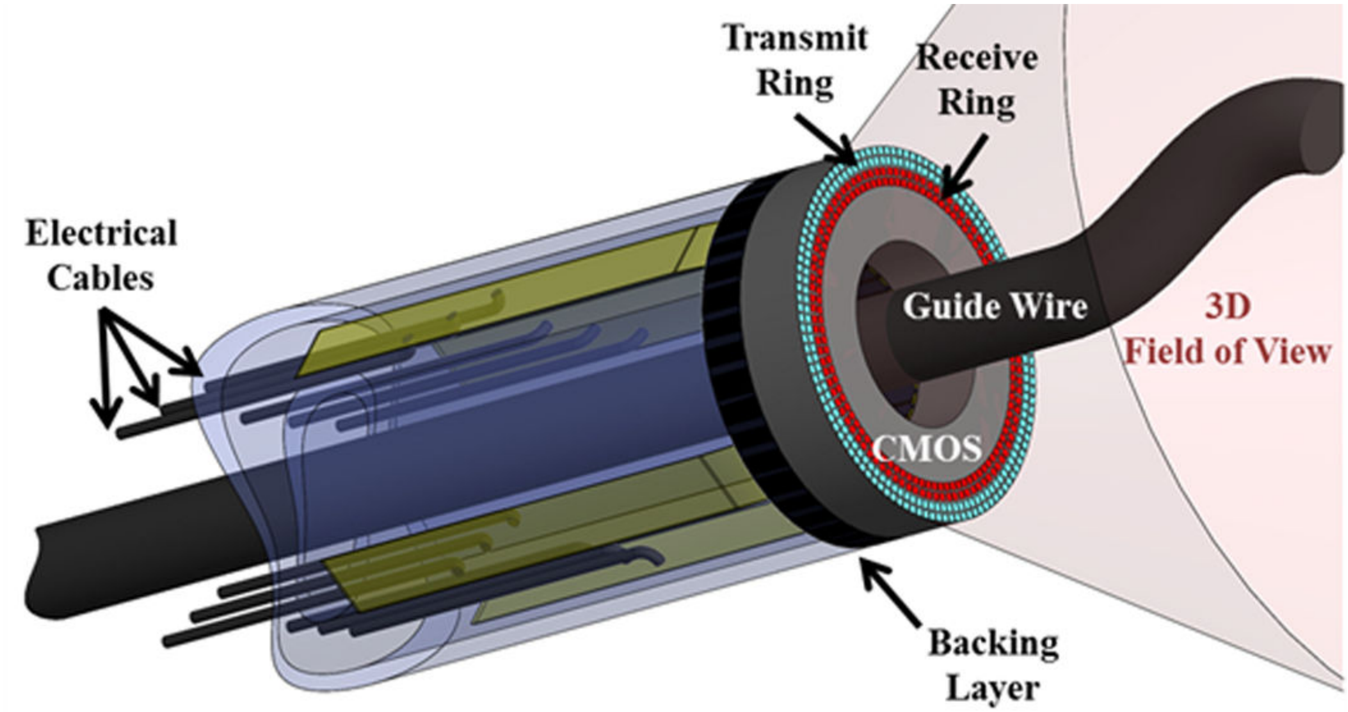

Figure 1.
Conceptual drawing of a single-chip fully-integrated forward looking ICE imaging catheter based on a dual-ring CMUT array monolithically integrated with the complete front-end CMOS IC.

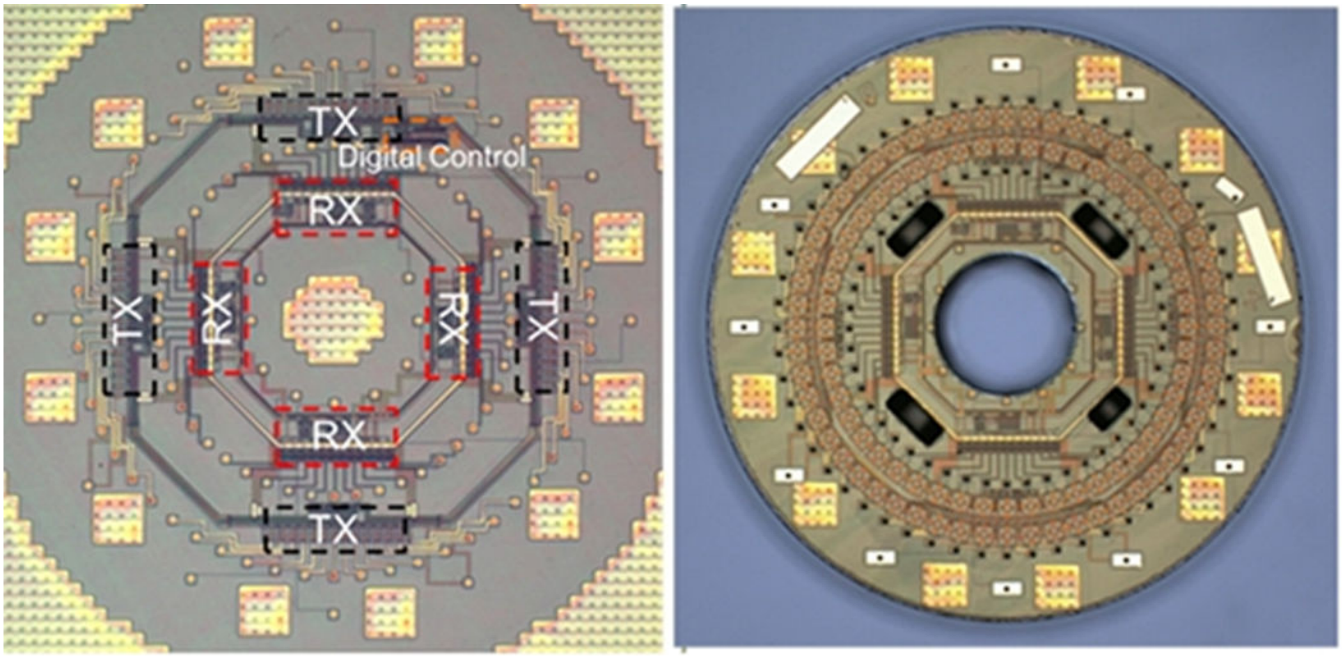

Figure 2.
Micrograph of the IC with receive and transmit electronics and the digital control circuitry (left). Monolithically fabricated single chip dual ring CMUT-on-CMOS array (right).

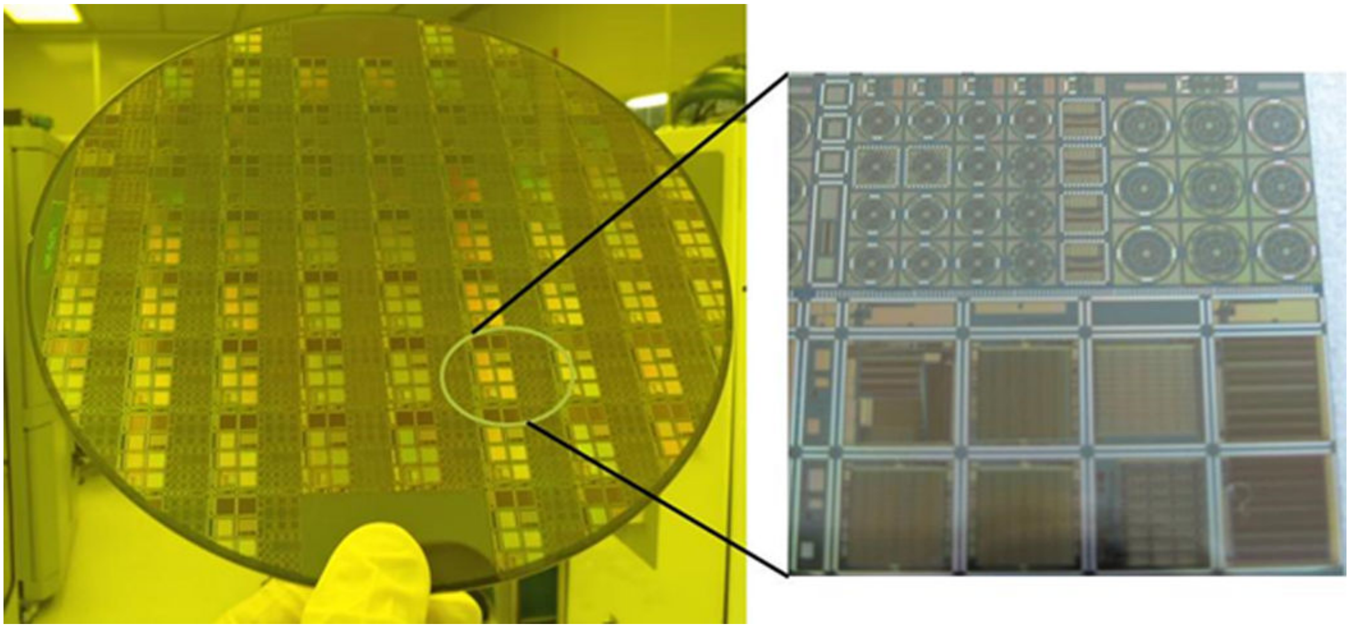

Figure 3.

(Left) The picture of the 8-inch CMOS wafer fabricated in 0.35-μm CMOS. (Right) Picture of the reticle of the wafer that contains the custom-designed ICs.

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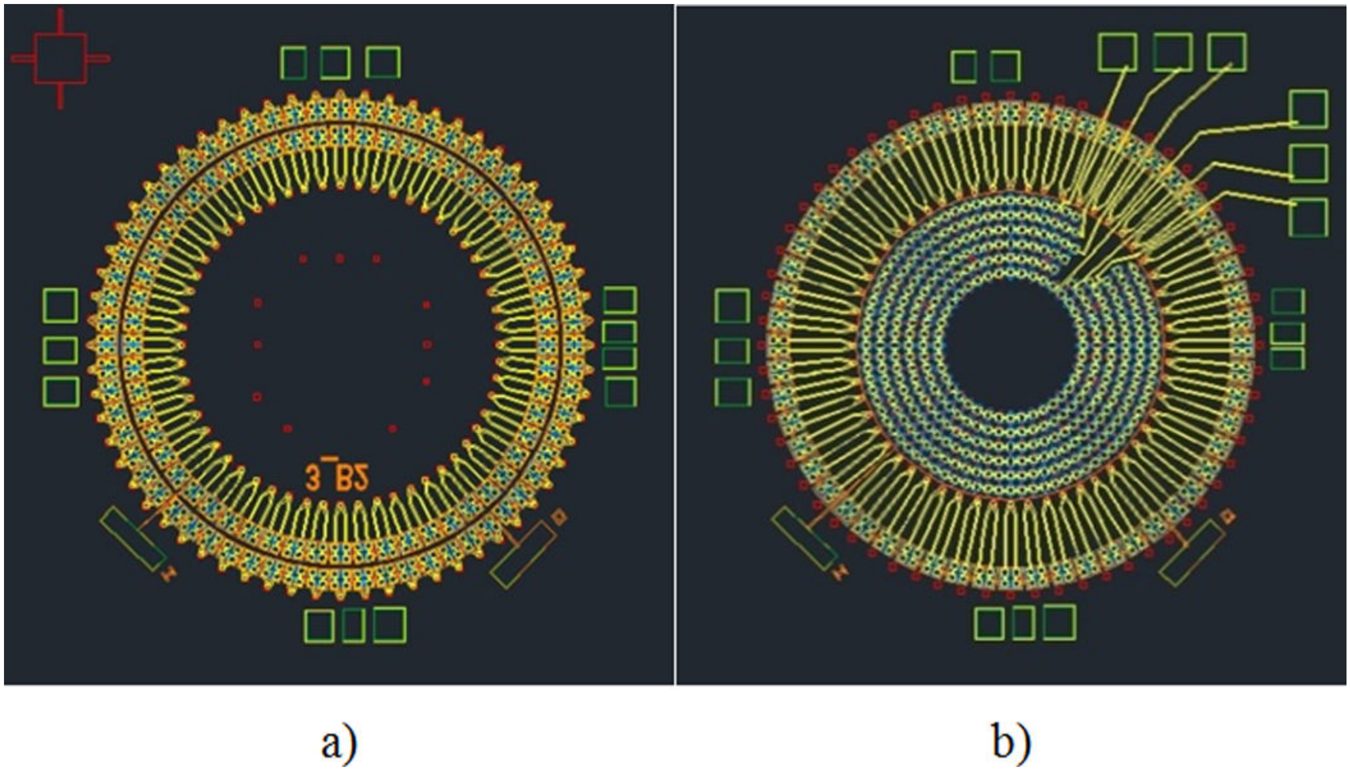

Figure 4.

Schematic description of fabrication masks for a) dual-ring device with transmit and receive array and b) proposed design with defocused annular transmit arrays and single ring receive array. In dual ring design receive array is inner ring with 56 elements where transmit ring is outer ring with 64 elements. The proposed design consists of 56 receive elements and 6 annular transmit ring arrays.

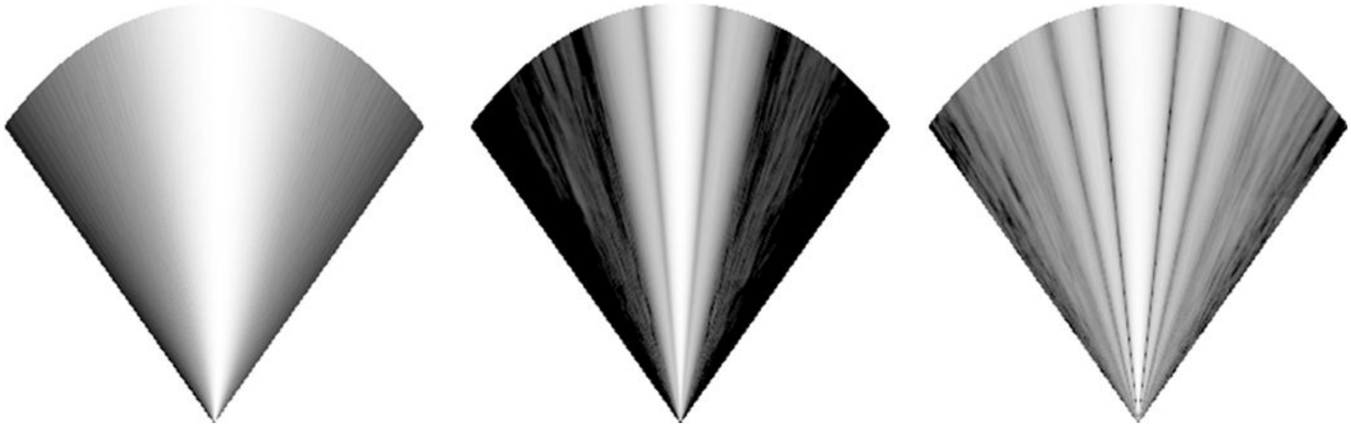

Figure 5.

Beam patterns in a 90 degrees sector a) single element b) nonfocused annular rings c) defocused annular rings

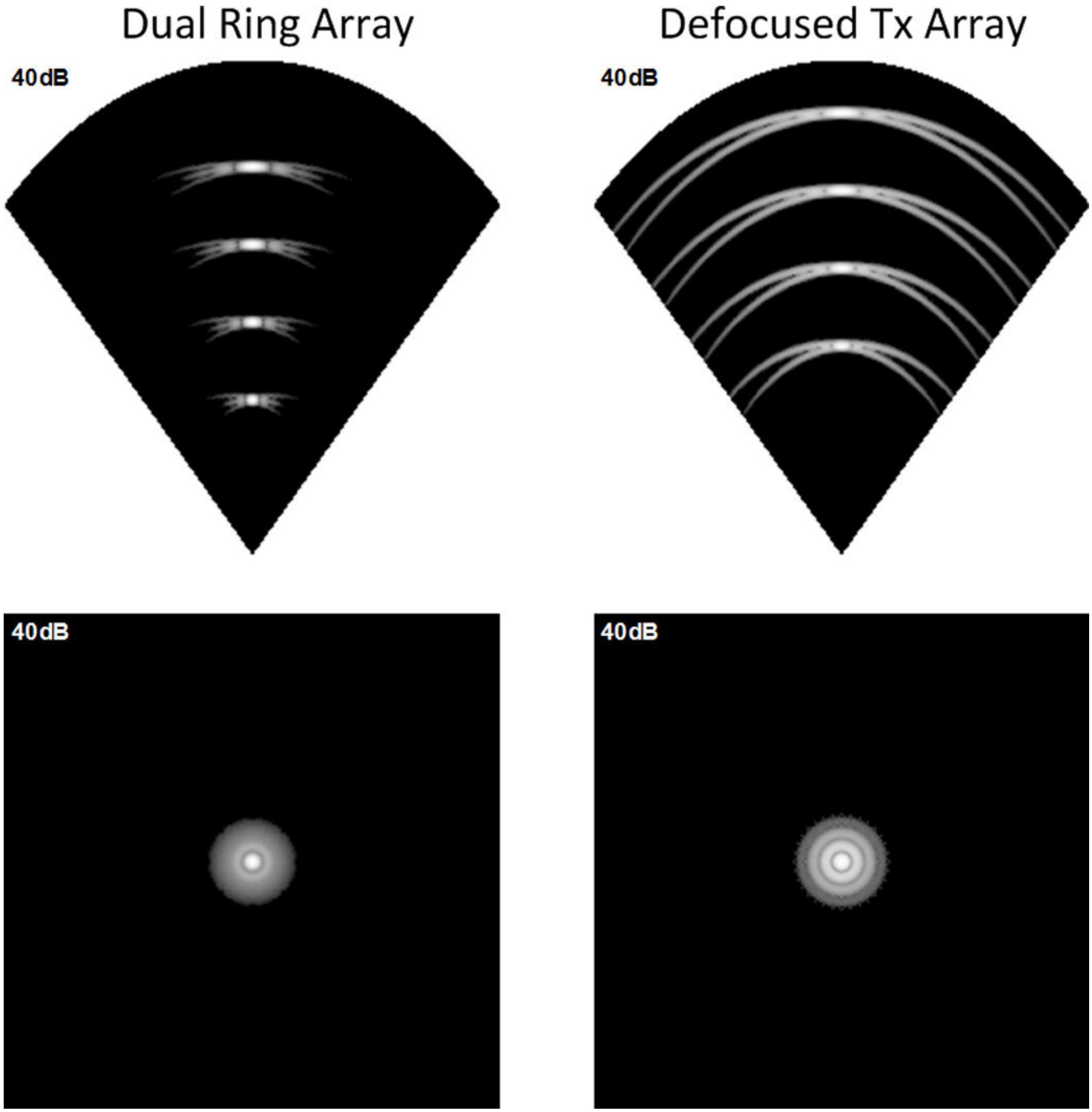

Figure 6.

Reconstructed 2-D PSFs. Top row: 2-D PSF for four point targets over $r\theta$-plane, where point targets are located on axis at 4 mm, 6 mm, 8 mm and 10 mm. Bottom row: 2-D PSF over $\theta\phi$-surface, where r=6 mm, $\pi/2\leq\theta\leq0$ (radial extension), and $2\pi\leq\phi\leq0$ (lateral extension).

Table 1

Quantitative Comparison of Array Configurations

	Dual Ring Army (ICE)	**Proposed Array**
Tx Elements	64	6 Defocused Annular Rings
Rx Elements	56	56
Center Frequency, Fract. BW	10 MHz, 50%	20 MHz, 50%
6-dB Lateral Resolution	@f/4 : 600 μm	@f/4 : 600 μm
Image Depth	40 mm	40 mm
Axial Resolution	150 μm	75 μm
Total Number of Firings	3584	56
Frame Rate (4 RF channels)	20 fps	1.3 kfps (No Averaging) 20 fps (64 Averaging)
Theoretical Image SNR	54 dB	60 dB
Motion Susceptibility	896 firings (4 RF channels)	14 firings (4 RF channels)