High-Intensity Focused Ultrasound (HIFU) Phased Arrays: Recent Developments in Transrectal Transducers and Driving Electronics Design

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Abstract. This work presents the design and characterization of 4 specific transrectal HIFU phased array transducers (9 to 826 elements, 2.0 to 4.0 MHz) for the non-invasive treatment of prostate diseases, and a general-purpose HIFU phased array driving electronics design capable of controlling up to 1024 channels. Four different HIFU phased arrays have been simulated during the last 3 years while investigating optimum array geometries, high-power transducer materials (piezoelectric and/or piezocomposite), interconnect structures, and excitation methods. The developed electronics were used to test three of the 4 arrays that have actually been fabricated, and were used to steer the HIFU beam in real time from 25 mm from the face of the array to 45 mm deep. The characteristics of these arrays and the results of these investigations are presented. The implementation details of the electronic driving system, consisting of a small footprint (25 cm x 25 cm) scalable architecture able to individually control the phase and amplitude of each channel (2 ns phase resolution, 7-bit amplitude resolution, 1024 maximum channel count), operate over a frequency range of 1 to 5 MHz, deliver up to 15 W of power to each channel, and drive elements with electrical impedances up to 2 kW are also presented. This flexible electronic driving system can be used to control a variety of HIFU phased arrays.

INTRODUCTION

The main purpose of this work is to develop HIFU phased array transducers and supporting electronics for clinical use in the non-invasive treatment of prostate cancer using the Sonablate® 500 HIFU system (Focus Surgery, Inc., Indianapolis, IN). Successful previous work in this area [1-5] has focused on proving the feasibility of therapeutic transrectal phased arrays and on the exploration of optimized array geometries. Current activities focus on the design and development of HIFU phased array transducers and systems suitable for commercial production. For this purpose, simulation, materials research, fabrication techniques, and electronics design activities were undertaken.

MATERIALS AND METHODS

A total of 3 annular HIFU phased arrays (capable of electronically focusing in depth, but requiring mechanical linear and sector motors to place lesions in longitudinal and transverse directions, respectively) were designed, built, characterized, and tested (Table 1, Columns 1-3). Such arrays fill the immediate need of being able to treat the prostate at different depths without requiring the insertion and re-positioning of probes containing different focal-length transducers. The results of these investigations have led to defining the concept of the 4th HIFU phased array (capable of electronically focusing in depth and length, but still requiring a sector motor to place lesions in the transverse direction). This array (Table 1, Column 4) is currently being considered for manufacture to fill a future need of a more reliable (requiring less steering) and general-purpose HIFU phased array-based system.

TABLE 1. Overview of Transrectal HIFU Phased Array Transducers and their Characteristics

Parameter	2.0 MHz Annular	2.8 MHz Annular	4.0 MHz Annular	4.0 MHz Cylindrical
Geometry	Spherical	Spherical	Spherical	Cylindircal
Aperture	40x22 mm	35x22 mm	50x22 mm	80x22 mm
Radius of Curvature	45 mm	35 mm	45 mm	40 mm
Num. of Elements	9 Rings	17 Rings	20 Rings	413 Channels
Operating Freq.	2.04 MHz	2.77 MHz	4.34 MHz	4.0 MHz
Material	N3B Ceramic (Keramos)	Piezo-Composite (Imasonic)	K270 Composite (Keramos)	K270 Composite (Keramos)
Imaging	Center Single 10 mm Element	Center Single 10 mm Element	Center Single 10 mm Element	Imaging Array
TAP (per cm^2 of array surface)	>5.5 W	>5.5 W	>10 W	>10 W estimated
Efficiency	70%	39%	51%	>50% estimated
Bandwidth	116 kHz (6%)	1.45 MHz (52%)	450 kHz (10%)	>20% estimated
Element Impedance	140Ω +/- 20Ω -47° +/- 6°	155Ω +/- 20Ω -60° +/- 7°	58Ω to 108Ω -23° to 53°	~1.5kΩ estimated
Cross-Coupling	Up to 50%	Up to 5%	Up to 5%	≤5% estimated
Acoustic Matching	None	Unknown	None	None
Backing	Air	Unknown	Air	Air

2.0 MHz Annular Array (9 Rings)

This annular array was developed to explore laser etching techniques to define arbitrary electrode shapes on PZT crystals, and to provide a medium-frequency HIFU phased array transducer to test the 1^{st} generation of high-power phased array driving electronics. Even though successful laser etching techniques were developed (Figure 1a), the array fell short of its simulated steering performance (in depth from z=30 mm to 50 mm) due to the extremely large inter-ring electrical cross-coupling (Figure 1b-d).

2.8 MHz Annular Array (17 Rings)

This annular array was developed to investigate the use of high-power piezocomposite materials for use in HIFU phased arrays, to experimentally verify the ability of annular arrays to focus over depths from z=20 mm to z=45 mm, and to quantify electrical and acoustic cross-coupling characteristics and compare them with those of PZT materials.

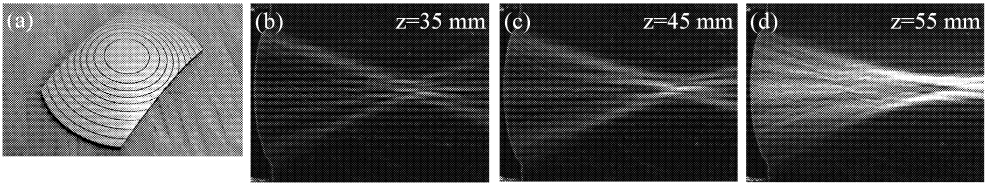

FIGURE 1. (a) 9-Ring Annular Array Crystal, and (b-d) Qualitative Evaluation of Focusing Ability of Array using Schlieren Imaging.

Due to the low electrical and acoustical inter-ring cross-coupling of the piezocomposite material, this array was able to focus the beam from z=20 mm to z=45 mm with little degradation of the focus (Figure 2b-d). The low efficiency of the piezocomposite material, however, required high driving powers and resulted in high front-face temperatures during operation.

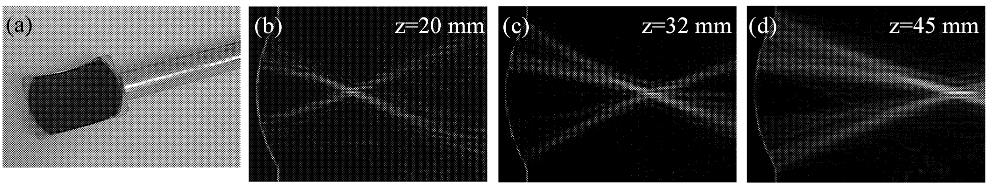

FIGURE 2. (a) 17-Ring Annular Array Transducer Assembly, and (b-d) Qualitative Evaluation of Focusing Ability of Array using Schlieren Imaging.

4.0 MHz Annular Array (20 Rings)

This annular array was developed to define piezocomposite forming techniques to manufacture curved HIFU phased arrays, to experimentally verify the focusing ability of annular arrays at the clinically proven excitation frequency of 4.0 MHz, to develop low-density interconnection strategies, and to investigate the suitability of alternate piezocomposite materials for HIFU phased array construction. Even though the initial fabrication procedures still need to be refined (the material cracked during the cooling phase, Figure 3a), the current results are encouraging. Additional work is required to refine electrode connections to the piezocomposite gold electrode, as connections deteriorated during the high-power focusing and testing of the array.

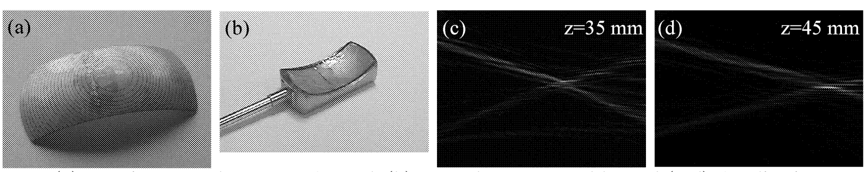

FIGURE 3. (a) 20-Ring Annular Array Crystal, (b) Transducer Assembly, and (c-d) Qualitative Evaluation of Focusing Ability of Array using Schlieren Imaging.

4.0 MHz Cylindrical Array Concept

The previous 3 designs rely on mechanical motion of the array (linear- and sector motions) to create a large lesion volume and to acquire treatment planning ultrasound imaging data. Ultimately, it is desired to avoid relying on any mechanical motion for both therapeutic and imaging functions. "Dual-mode" [6,7] arrays, capable of both imaging and therapy functions, are constructed of high-power piezocomposites, and are currently being investigated to remove at least the linear motion component. Current simulations show that this goal can be achieved with a 80 mm long and 22 mm wide cylindrical HIFU array (6 element rows) made of piezocomposite material utilizing electronically controlled sub-apertures (variable) for therapeutic focusing in depth (z=25 to 45mm) and longitude (x=-20 to +20 mm), as shown in Figure 4. The 2D imaging function would be implemented by electronically scanning a small sub-aperture (inner 2 rows only) to acquire 1D RF-lines (to reduce electronic complexity) that are then combined to form the full 2D image (x=-40 to +40 mm, z=0 to 60 mm), as shown in Figure 5.

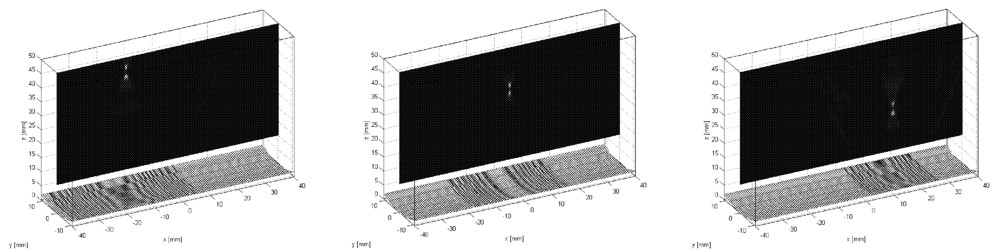

FIGURE 4. Longitudinal Steering using Subapertures, and Depth Focusing using variable-size Subapertures to maintain a fixed f-number and eliminate off-axis steering gain loss.

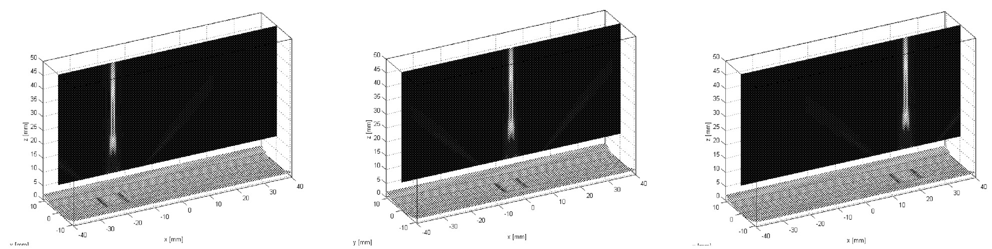

FIGURE 5. Linear Mechanical Imaging Function replacement with Electronically-controlled Imaging using Imaging Subapertures (2D Image = assembly of 1D RF-lines; 2-4 frames/second expected).

HIFU Phased Array Driving Electronics

General-purpose HIFU phased array driving electronics were developed to support the array design, characterization, and test efforts. It was extremely important that these electronics be easily customizable to a wide variety of HIFU phased arrays, and that they should be small enough to fit inside the current Sonablate® 500 HIFU system (Focus Surgery, Inc.). The driving electronics have the following specifications:

- Small Footprint Digital/Analog Board Pair (25x25x4 cm).
- 64 Channels/Board, Stackable/Scalable to up to 1024 Channels Total.

- 2 ns Phase Resolution (8-bit Control, Digital Delay Line).
- 7-bit Amplitude Resolution (Digital Pulse-Width Modulator).
- 1-5 MHz Operating Frequency (Programmable).
- CW Operation, Programmable ON/OFF Time.
- Individual Impedance Matching and Filtering for each Channel.
- Capable of driving Elements up to 2 kW Impedance.
- Individual Channel Power Monitoring (Forward Power).
- Controlled over a Single Digital Computer Interface (Nat. Instr. Digital I/O Board).
- Input Power: 5V (4 A), 9 V (2 A), 0-75 V (up to 6.5 A) per Board Pair.
- Low-Power (<2.5 W/Channel) and High-Power (<15 W/Channel) Implementations.

A block diagram showing the digital section of the electronics that controls the phase (through a digital delay line) and amplitude (through a digital pulse-width modulator) for each channel is shown in Figure 6. The digital section is connected to an analog section that amplifies the CW signal (through a MOSFET amplifier), provides signal filtering (through a 5th order low-pass filter), and an impedance matching network for each channel using an impedance matching transformer.

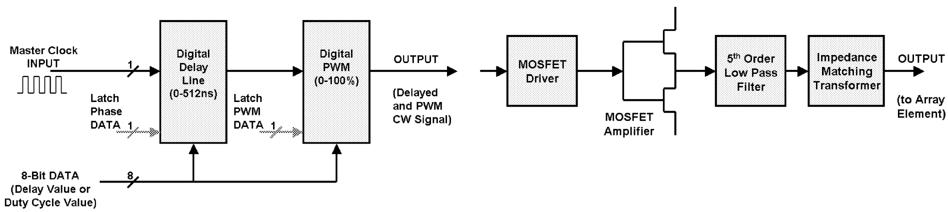

FIGURE 6. Digital (left) and analog (right) block diagrams of array driving electronics (one channel).

The efficiency of the analog amplifying electronics is between 70-80%. Two complete systems have been built: a 20 channel high-power system used to characterize and drive all developed annular arrays to date, and a 320 channel low-power system, in preparation for characterization and driving activities of high-element count HIFU phased array transducers (Figure 7). The developed electronics have met all expectations, and provide the required flexible building block for all future HIFU phased array transducer design activities at Focus Surgery, Inc.

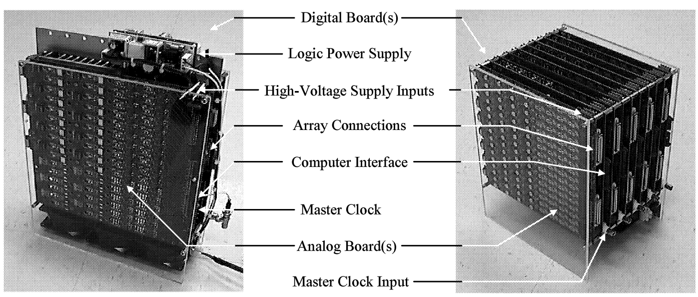

FIGURE 7. 20 Channel High-Power System (left) and 320 Channel Low-Power System (right).

CONCLUSIONS

Piezocomposite materials are required to manufacture HIFU therapeutic phased array transducers that require curved surfaces, arbitrary electrode patterns, and elements capable of performing both therapeutic and imaging functions (low cross-coupling, medium-bandwidth). Current piezocomposite power densities >10 W (per cm^2 of array surface) seem to be adequate to generate the required HIFU intensities at the electronically-controlled foci of spherical as well as cylindrical geometries. It should be possible to make up for the loss in focusing gain (due to off-axis steering/focusing) of these geometries of up to a factor of 3 by driving the array at higher power levels (with proper array surface cooling). Improving piezocomposite material efficiencies will help. The ability to control 1000+ channels with small and versatile electronics minimizes this loss in focusing gain, since it is always better to "move the array" (electronically, using a subaperture) than to electronically steer the focus off-axis. Large channel counts also provide a tool to eliminate the mechanical motion component of current single-element and array HIFU systems. Maintaining the imaging component in therapeutic systems is essential for all future applications of HIFU. Research continues to define the geometry and material of choice for Sonablate® 500 incorporation and clinical validation.

ACKNOWLEDGEMENTS

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