CURVED ANNULAR ARRAY TRANSDUCERS MADE FROM COMPOSITE PIEZOELECTRIC MATERIALS

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Spherically curved annular array transducers have been developed using a composite piezoelectric material. The composite material allows the construction of sensitive and high-resolution arrays with elements defined by the electrode pattern alone. The array elements exhibit uniform properties and clean thickness-mode oscillations uncoupled to spurious lateral resonances. A prototype 3 MHz array exhibits a minimum insertion loss of 8 dB with a 6 dB fractional bandwidth of 57%. The -20 dB and -40 dB ringdown times in this array correspond to 3.3 and 6.2 periods, respectively.

INTRODUCTION

Annular array transducers, incorporating electronic focusing, provide unique capabilities in medical ultrasonic imaging. By adjusting the time delays between the elements, the transmitted pulse can be focused at a desired distance along the transducer axis. On reception, the focal depth can be rapidly adjusted so that the echo signal is always in focus. Compared to a single element disk transducer, which is in focus at only one depth, annular arrays provide a sharp acoustic image over the entire imaging range.

The fabrication of annular arrays from the conventional PZT-type ceramics involves several difficulties. The criteria for sharp acoustic focusing results in the width of the rings being close to the transducer thickness; that, in turn, leads to a coupling of the desired thickness mode to spurious lateral modes. Forming the transducer in the shape of a spherical cap simplifies the electronics and acoustic design of annular arrays; achieving this with rigid, brittle ceramics is not easy. In addition, acoustic isolation between the array elements requires slotting of the ceramic between the elements.

Composite piezoelectric materials are particularly suitable for annular array transducers.[1-8] They are readily formed into curved shapes. Array elements can be defined by the electrode pattern alone - no slotting is needed to achieve acoustic isolation. The individual elements exhibit clean thickness mode oscillations, uncorrupted by spurious lateral resonances. In addition, composite arrays provide better axial resolution due to their inherently shorter impulse response. This paper illustrates these properties with a 3 MHz annular array transducer formed on a spherically curved composite disk.

FABRICATION

The dice-and-fill fabrication of rod composites has been previously described.[9,10] This technique has been further developed[11] to form the composites in the shape of a spherical cap. In the fabrication process, an array of thin piezoelectric rods is formed by cutting grooves into a PZT ceramic disk. A composite structure is then obtained by casting a polymer into these grooves. While the polymer is partially cured, the composite structure is compression molded to a spherical shape, and ground to a final size.

Prototype annular arrays were formed on spherically curved composite disks of 100 mm radius of curvature. The array elements were defined on the convex face by scribing the electrode without dicing the composite material. The array was provided with a quarter wavelength matching layer (Z = 3 Mrayl) and a light backing (Z = 1.4 Mrayl). A schematic diagram of an assembled array is shown in Figure 1.

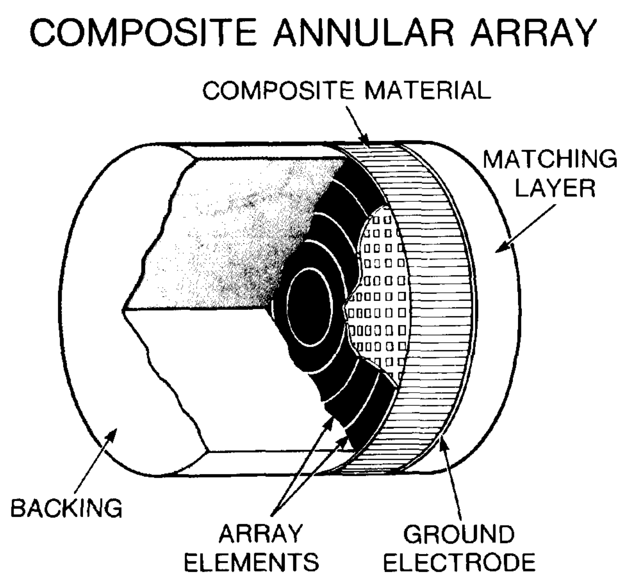

FIGURE 1 Cut-away diagram of spherically curved annular array made from composite piezoelectric material. The hidden front surface is concave.

MATERIAL PARAMETERS

The properties of the composite material relevant to its performance as a thickness-mode transducer were measured in the complete disk, and in the individual elements of the annular array after scribing the electrode. These measurements were made before attaching the backing and matching layers. Analysis of the electrical impedance of the air loaded transducer in the vicinity of the thickness resonance yielded the thickness electromechanical coupling coefficient, k_t, sound velocity, v^D, clamped dielectric constant, ε^S, mechanical quality factor, Q_m, and the dielectric loss, tan δ.

Figure 2 shows the magnitude of the electrical impedance of the individual elements as a function of frequency. Outer rings show smaller impedance because of their larger area. These curves indicate clean thickness mode resonances uncoupled to spurious lateral modes. Analyses of these measurements yield the material parameters listed in Table I. These data indicate uniform properties of the array elements. The small difference between the coupling coefficients of the center disk and the rings may be attributed to the different shapes and boundary conditions of these elements. The apparently large variations in the mechanical Q of the elements have no significant effect on the transducer performance. These variations may also be attributed to the different boundary conditions of the elements.

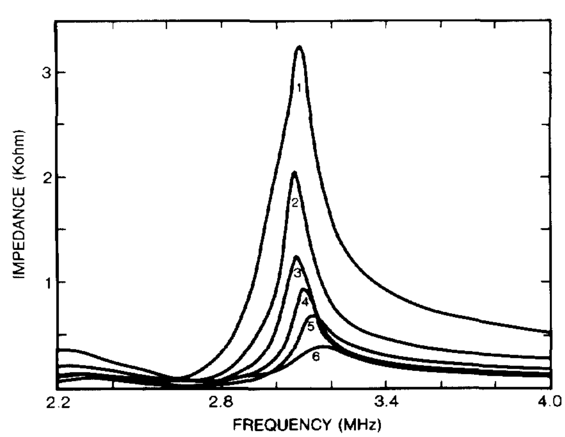

FIGURE 2 Electrical impedance versus frequency for the central disc (curve 1) and five ring elements of the prototype 3 MHz annular array.

TABLE I
Material Parameters for Individual Elements and Total Aperture

	central disk	1st ring	2nd ring	3rd ring	4th ring	5th ring	full disk
v^D (m/sec)	3680	3680	3670	3720	3740	3790	3700
k_t	.55	.52	.51	.52	.52	.51	.57
Q_m	23	30	29	29	24	18	33
ε^S	470	470	470	470	460	490	470
tan δ	.05	.05	.05	.04	.05	.05	.05
f_0 (MHz)	3.07	3.07	3.06	3.10	3.12	3.15	3.08

TRANSDUCTION PROPERTIES

The impulse response characteristics and the round trip insertion loss were measured for the whole aperture of the array. These measurements were performed in a water tank with a steel block located at the focal zone. Electrical matching of the transducer to the source was accomplished with a series inductance (1.5 μH) and adjustment of the output resistance of the source to the resistance of the transducer near the resonance (about 25 ohms).

Figure 3 shows the round-trip insertion loss as a function of frequency and the impulse response in the time domain. The minimum insertion loss is 8 dB, with a 6 dB fractional bandwidth of 57%. The impulse response characteristics are listed in Table II together with the corresponding characteristics of a conventional solid PZT annular array.

Evidently, the -40 dB ringdown time in the composite transducer is significantly shorter. However, in making such a comparison one should keep in mind that the performance of a transducer depends not only on the transducer material but also on the transducer design and the electrical network used to transmit and receive the signals. Table II compares the performances of certain designs of composite and solid ceramic transducers as obtained without optimization of the transmit-receive electronics.

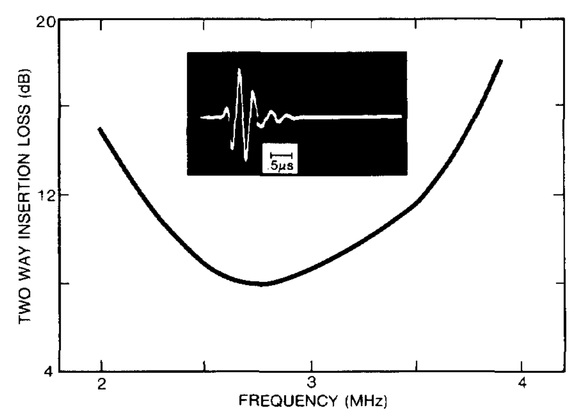

FIGURE 3 Measured two-way insertion loss versus frequency and (inset) measured two-way impulse response for the prototype 3 MHz annular array.

TABLE II
Device Characteristics of Composite and Solid Ceramic Annular Arrays

	Composite	Solid Ceramic
Center Frequency at -6 dB (MHz)	2.9	2.83
Center frequency at -20 dB (MHz)	2.9	2.85
-6 dB fractional bandwidth (%)	57	58.4
-20 dB fractional bandwidth (%)	100	94.7
-20 dB pulse length (μsec)	1.15	1.3
-40 dB pulse length (μsec)	2.15	3.3

ARRAY CROSS TALK

Low cross coupling between the array elements is seen through the radiation patterns of individual elements in the array. As an illustration, Figure 4 shows the CW radiation pattern for a single ring of the prototype array. The solid curve represents the theoretical prediction for an isolated element of the same geometry. This curve is calculated using the directivity function, $D(\theta)$, of a ring in a rigid baffle, namely,

$$D(\theta) = 2\,[\,a_2 J_1(ka_2 \sin\theta) - a_1 J_1(ka_1 \sin\theta)\,] / k\,(a_2^2 - a_2^2)\sin\theta,$$

where $k = 2\pi/\lambda$ is the wave-number, J_1 is the Bessel function of the first kind order one, and a_1, a_2 are the inner and outer radii of the ring, respectively. The experimental data and the theoretical curve are in good agreement, indicating that the acoustic excitation is essentially confined to the geometrical dimensions of this element.

FOCUSING

Focusing properties were measured on a five element 3.5 MHz prototype annular array before the attachment of backing and matching layers. Five separate pulse generators were used to excite the elements with a single cycle sine wave at 3.5 MHz. The pulse generators were triggered at the appropriate times by sending the triggering pulse through variable delay lines.

In this array the areas of the elements are different and consequently their input electrical impedances are different. To ensure a constant input power density across the array, the output voltage of each pulse generator was adjusted to obtain the same voltage signal across each element. This condition ensures that the input power for each element is proportional to the area of the element.

Directivity measurements were performed at different depths before and after beam forming with the electronic lens. Using these data, the widths of the acoustic beam at the -6 dB and -20 dB levels were plotted as functions of the axial distance.

Figure 5 shows the one-way beam width as a function of the axial distance when all five elements were excited simultaneously (no electronic focusing). The focusing action of the spherically curved transducer is clearly observed. An acoustic focus is obtained at a distance of 8.5 cm from the transducer. The beam widths at the -6 dB and -20 dB levels are 3.5 mm and 8.4 mm, respectively. Figure 6 shows the beam widths obtained by exciting the elements with the electronic delays appropriate for a focus at 5 cm. The effects of the electronic lens are clear: the focus shifted and the beam is narrower. A minimum beam width at half maximum of 2.3 mm is obtained at a depth of 5 cm. The -20 dB beam width at this position is 5.8 mm. The latter decreases to a minimum value of 4.6 mm at an axial distance of 6 cm.

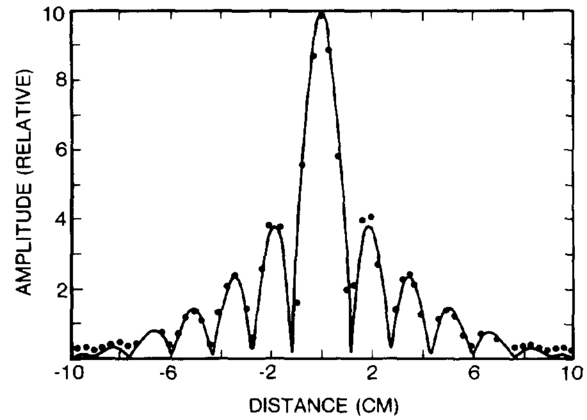

FIGURE 4 Measured CW radiation pattern from the second ring element of the prototype 3 MHz array (points) and calculated radiation pattern for an isolated element with the same geometry.

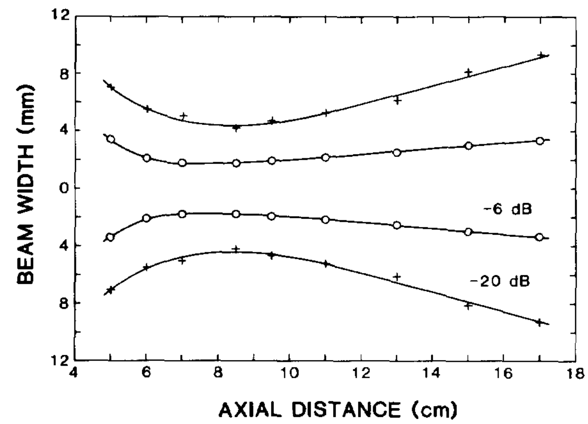

FIGURE 5 One-way beam width versus axial distance for the prototype 3.5 MHz spherically-curved annular array without electronic focusing.

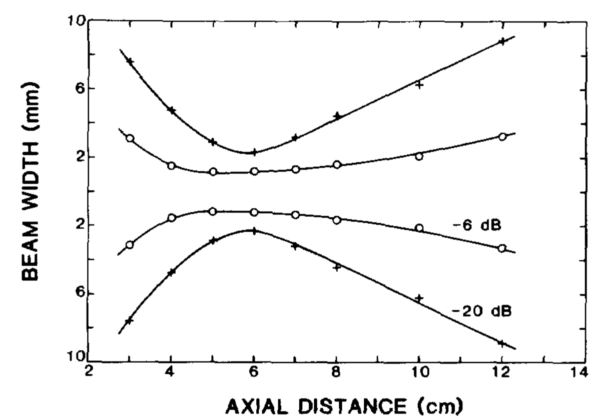

FIGURE 6 One-way beam width versus axial distance for the prototype 3.5 MHz spherically-curved annular array with electronic focusing at 5 cm.

The theoretical beam widths in the focal zone can be estimated using the following approximations:

$$-6 \text{ dB Beam Width} \sim 1.4cF/Df,$$

$$-20 \text{ dB Beam Width} \sim 4cF/Df,$$

where D is the transducer diameter, f is the center frequency of transmitted sound, c is the speed of sound in the propagation medium, and F is the focal length. For D = 15 mm, f = 3.5 MHz, and c = 1500 m/s, we obtain -6 dB beam widths of 2.0 mm and 3.4 mm, and -20 dB beam widths of 5.7 mm and 9.7 mm at the focal lengths of 5.0 cm and 8.5 cm, respectively. These approximated results agree within 15% with the experimental data given above.

DISCUSSION

Our results show that rod composites are suitable for the design of an undiced spherically curved annular array. The array shows low cross coupling between neighboring elements and good transduction and focusing properties. This understanding has spread outside the research community. An eight-element 7.5 MHz annular array made from piezocomposites has been described by Echo Ultrasound.[12] Precision Acoustic Devices has developed composite annular arrays spanning the 2.5 to 7.5 MHz range,[13] while Acoustic Imaging has converted their product line of annular arrays, also ranging from 2.5 to 7.5 MHz, over to piezocomposites.[14] Moreover, Ferroxcube Division of Amperex Electronic Corporation is prepared to manufacture composite material suitable for ultrasonic transducer applications.[15]

It is instructive to note that some of the advantages of composite materials for annular arrays were found by earlier workers.[16] A disk transducer was diced in two directions ninety percent through and the grooves were filled with a polymer, yielding a composite material. Annular array elements were defined by the electrode pattern alone. The array exhibited good acoustic isolation between elements and a well focused beam pattern. No sensitivity measurements were reported and the impulse response shown was rather long. These deficiencies are likely due to an unoptimized composite and absence of an acoustic matching layer.

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