ULTRASONIC TRANSDUCER ARRAYS MADE FROM COMPOSITE PIEZOELECTRIC MATERIALS

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ABSTRACT

The performance of composite linear arrays with elements defined by electrode patterning alone is described. The prototype arrays (4.5 MHz, 1mm pitch) show low cross coupling between neighboring elements, good sensitivity over a broad frequency range, and exceptionally short ringdown times. High quality images of a test object are produced by a composite array provided with electronic and mechanical lenses.

I. Introduction

Linear array transducers are employed in medical ultrasound imaging systems to produce real time scanning in a rectangular format [1]. These arrays consist of a large number of piezoelectric elements arranged side by side. A rectangular scan at a high repetition rate is accomplished by electronic switching of a subset of elements ("an aperture") along the length of the array. Different techniques are employed to focus the acoustic beam in the orthogonal elevation and scan planes. In the elevation plane, a fixed focus is provided by a mechanical lens that covers the array. Focusing in the scan plane is accomplished electronically by addressing the elements within the aperture with appropriate time delays such that a constructive interference occurs at a particular depth (the focal point).

Linear arrays are commonly made from a long strip of a PZT ceramic by cutting it into a number of plank shaped elements [2]. To obtain a unimodal vibration of the elements each element is further subdiced into several subelements with a width to thickness ratio less than unity. Recently, modified lead-titanate ceramics with extremely low planar electromechanical coupling factor have been proposed to circumvent the need for subdicing array elements [3-5]. Both, the PZT and lead-titanate ceramics have high electromechanical coupling factor ($k_t \approx 0.5$), however, their high acoustic impedance ($Z \approx 30$ Mrayl) makes coupling to tissue ($Z \approx 1.5$ Mrayl) difficult.

Elimination of dicing altogether has been achieved with piezoelectric polymers such as polyvinylidene difluoride (PVDF) and its copolymers [6,7]. These polymers have the additional advantage of low acoustic impedance ($Z \approx 4$ Mrayl) which simplifies broadband coupling to tissue. However, the performance of such transducers is presently limited by the low electromechanical coupling factor ($k_t \leq 0.3$), low dielectric constant (≈ 10) and large dielectric loss ($\approx 15\%$) of the polymers.

In previous papers [8,9] we have shown that composite materials, consisting of a piezoelectric ceramic and a passive polymer, combine the desired properties of high electromechanical coupling factor and low acoustic impedance. In addition, measurements in preliminary composite arrays indicated that low interelement cross coupling can be achieved with array elements defined by electrode patterning alone. This combination of properties makes the composite materials suitable for the design of sensitive and high-resolution transducer arrays for medical ultrasound imaging.

In this paper we describe the design and performance of prototype composite arrays operating at 4.5 MHz. Following the characterization procedure outlined by Pesque, Coursant and Mequio [10], we review the transduction properties, cross-talk level, and focusing properties of the arrays. In addition, we present an acoustic image of a test object produced by a composite array provided with a combination of mechanical and electronic lenses. The results of these experiments will be demonstrated with two composite arrays referred to as CA1 and CA2.

II. Fabrication Technique

The arrays (4.5 MHz, 1mm pitch) were formed on rectangular plates of a composite material in which a polymer matrix holds thin rods of PZT ceramic parallel to each other and perpendicular to the faces of the plate [8,9]. The material parameters describing the thickness-mode oscillation in these composites are listed in Table I. After coating the faces of the composite plates with electrodes, a Kapton foil containing the leads was attached to the back surface of the plates. Array elements were defined on this surface by scribing the Kapton foil and the electrode without dicing the composite material (Fig. 1). The arrays were provided with a quarter wavelength matching layer of Mylar and a light backing ($Z = 1.4$ Mrayl).

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Table I. Properties of Composite Plates CA1 and CA2.

	CA1	CA2
Dielectric constant, ε^T	250	330
Sound velocity, v^D (m/s)	3590	3660
Thickness coupling coeff. k_t	0.47	0.51
Mechanical quality factor, Q_m	9	9
Acoustic impedance, Z (MRayl)	10	10

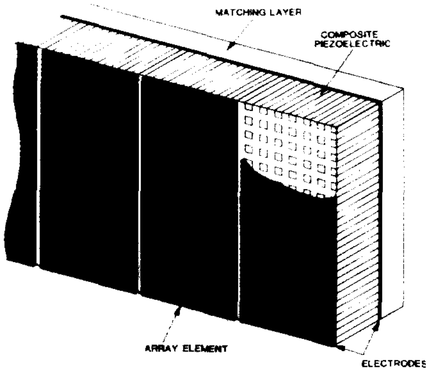


Fig. 1. Composite linear array with elements defined by electrode pattern alone.

III. Experimental Results

Electrical Impedance. Figure 2 shows the magnitude of the electrical impedance as a function of frequency for a single element in a composite array loaded by water. The impedance curve reveals a unimodal vibration without spurious resonances.

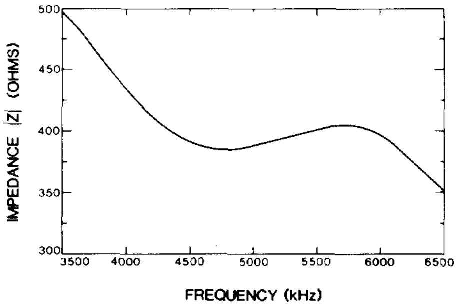
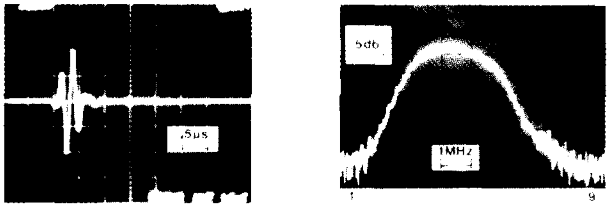


Fig 2. Electrical impedance vs frequency for a single element in composite array loaded by water.

Sensitivity and Ringdown Times. The impulse response characteristics and the round trip insertion loss were measured for an aperture of 16 elements with the array placed in a water tank at a distance of 5 mm from a steel block. The results of these measurements are summarized in Table II. Both arrays exhibit short ringdown times and good sensitivity over a broad frequency band. A minimum insertion loss of 13.2 dB and 10.5 dB with a 6 dB fractional bandwidth of 68% and 62% are obtained for arrays CA1 and CA2, respectively. Exceptionally compact impulse response is exhibited by array CA1 (Figure 3). The -20 dB and -40 dB ringdown times measured in this array correspond to 3.1 and 5.5 periods, respectively.

Table II. Summary of Impulse Response Characteristics and Insertion Loss of an Aperature of 16 Elements in Composite Arrays CA1 and CA2.

	CA1	CA2
Center freq. at -6 dB F_c (MHz)	4.4	4.6
Center freq. at -20 dB F'_c (MHz)	4.4	4.8
-6 dB Fractional bandwidth $\Delta F/F_c$(%)	68	62
-20 dB Fractional bandwidth $\Delta F/F'_c$(%)	106	106
-20 dB Pulse length (μsec)	0.7 (3.1T)	0.65 (3T)
-40 dB Pulse length (μsec)	1.25 (5.5T)	1.6 (7.5T)
Minimum insertion loss (dB)	13.2	10.5



(a) (b)

Fig. 3. Impulse response of 16 elements aperture in composite array in time domain (a) and frequency domain (b).

Cross Talk. Electrical measurements of cross talk were performed by exciting one element of the array with a single-cycle sine wave and measuring the voltage generated on adjacent elements with a high impedance scope probe. Table III lists the cross coupling indexes calculated as 20log(Vc/Ve), where V_e and V_c are the peak to peak amplitudes of the excitation and cross talk signals, respectively. The data of Table III indicate a high degree of isolation between neighboring elements. It is important to note that even this small amount of cross coupling is electrical. Improved device fabrication procedure could reduce that even further.

Table III. Cross Coupling (dB) in Composite Arrays CA1 and CA2.

	Array CA1		Array CA2	
	Elec.	Mech.	Elec.	Mech.
1st Neighbor	-33.5		-39	
2nd Neighbor	-39	-52	-41	-50
3rd Neighbor	-43	-55	-44	-54

This low cross talk was further confirmed by measurements of the directivity pattern of individual elements in the arrays. Figure 4 shows the acoustic beam pattern generated by exciting a single element (width 0.95 mm) with a tone-burst. The solid curve in this figure corresponds to the theoretical beam pattern calculated for an isolated element of width 0.95 mm surrounded by a soft baffle [11]. The agreement between the experimental data and the calculated curve indicates that the acoustic excitation is essentially confined to the geometrical width of the element.

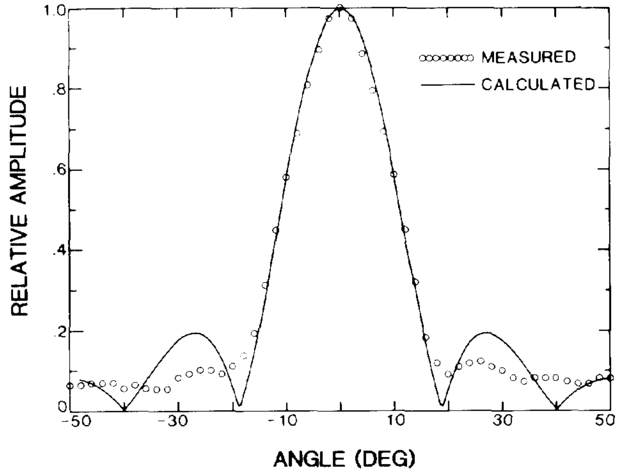


Fig. 4. Measured cw radiation pattern from a single element (width 0.95 mm) in composite array. Solid curve calculated for isolated element of the same width.

Beam Forming. Focusing experiments were conducted with an electronic lens of 8 elements focusing at an axial distance of 50 mm. Figure 5 shows the cw beam patterns measured in the focal plane before and after beam forming with the electronic lens. The focusing effect is clearly observed; moreover, the measured beam pattern for the electronic lens agrees well with the theoretical prediction (solid line in Figure 5).

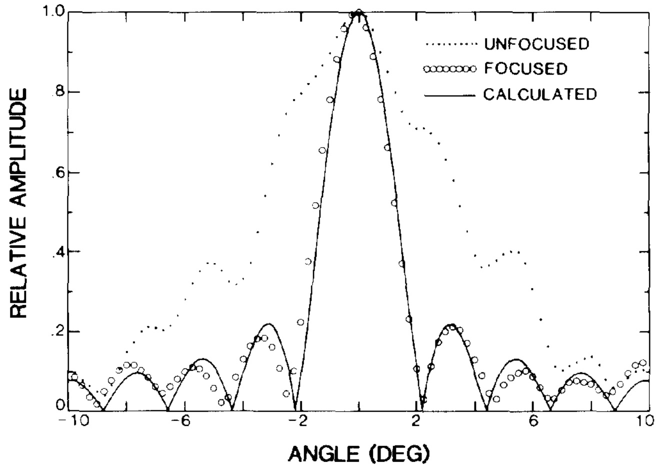


Fig. 5. Measured (circles) and calculated (solid line) cw beam patterns for electronic lens comprising 8 elements. The dotted line shows beam pattern measured without electronic lens.

Acoustic Images. Image quality tests were performed with a composite array combining mechanical and electronic focusing in two orthogonal planes. The mechanical lens, in the form of a rubber plane-cylinder, focused the acoustic beam at a depth of 50 mm in the elevation plane normal to the scan plane. An electronic lens focused the beam at 50 mm in the scan plane. Figure 6 shows an image of a test object (Ecobloc foam) generated with the composite array when the same electronic focusing was applied in the transmission and reception cycles. A high image quality is obtained as expected from the focusing properties and the impulse response characteristics of the composite array.

Fig. 6. Image of Ecobloc foam taken with a composite array.

IV. Discussion and Conclusions

The construction of arrays with elements defined by electrode patterning alone is a relatively simple and flexible process. Attempts to fabricate such undiced arrays (4 MHz, 1mm pitch) using conventional PZT ceramics yielded distorted directivity patterns for individual elements which led to a degraded performance of the electronic lens [10]. This phenomenon is due to coupling between elements caused by mechanical and electrical fringing effects [12]. These effects become more pronounced as the pitch of the array becomes smaller compared to the thickness of the array and the wavelength in the propagation medium. The electrical and mechanical coupling effects are largely suppressed in the composite structure of ceramic rods and polymer. The large dielectric anisotropy in the composites ($\varepsilon_{33}^T \approx 300$, $\varepsilon_{11}^T \approx 4$) suppresses cross coupling due to electrical fringing. Likewise, the large attenuation and low sound velocity in the lateral direction, normal to the ceramic rods, reduce the effects of mechanical cross coupling. The composite materials have the additional advantages of low acoustic impedance and high electromechanical coupling coefficient. This combination of properties makes the composite materials suitable for the design of sensitive and high resolution undiced arrays.

The simple design of undiced composite arrays described in this paper yields low cross coupling between neighboring elements, good sensitivity, and exceptionally compact impulse response. High quality images are produced with these arrays. The performance of composite arrays can be further improved by optimizing the ceramic and polymer components of the composite material [13], and the acoustic matching to the propagation medium.

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