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Micromachined high frequency PMN-PT/epoxy 1–3 composite ultrasonic annular array

Changgeng Liu [a,*], Frank Djuth [a], Xiang Li [b], Ruimin Chen [b], Qifa Zhou [b], K. Kirk Shung [b]

[a] Geospace Research, Inc., 525 South Douglas Street, Suite 290, El Segundo, CA, USA
[b] Dept. of Biomedical Engineering, University of Southern California, Los Angeles, CA 90245, USA

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ABSTRACT

This paper reports the design, fabrication, and performance of miniature micromachined high frequency PMN-PT/epoxy 1–3 composite ultrasonic annular arrays. The PMN-PT single crystal 1–3 composites were made with micromachining techniques. The area of a single crystal pillar was 9 × 9 μm. The width of the kerf among pillars was ∼5 μm and the kerfs were filled with a polymer. The composite thickness was 25 μm. A six-element annular transducer of equal element area of 0.2 mm^2 with 16 μm kerf widths between annuli was produced. The aperture size the array transducer is about 1.5 mm in diameter. A novel electrical interconnection strategy for high density array elements was implemented. After the transducer was attached to the electric connection board and packaged, the array transducer was tested in a pulse/echo arrangement, whereby the center frequency, bandwidth, two-way insertion loss (IL), and cross talk between adjacent elements were measured for each annulus. The center frequency was 50 MHz and −6 dB bandwidth was 90%. The average insertion loss was 19.5 dB at 50 MHz and the crosstalk between adjacent elements was about −35 dB. The micromachining techniques described in this paper are promising for the fabrication of other types of high frequency transducers, e.g. 1D and 2D arrays.

1. Introduction

Until recently most medical high-frequency (>30 MHz) ultrasound imaging systems are based on single-element transducers, which are either unfocused or geometrically focused at a certain fixed depth. The fixed focus imposes limitations on lateral resolution and depth of field (DOF). Linear arrays and 2-dimensional (2-D) arrays are desired for their capabilities in beam steering, dynamic focusing, and higher image frame rate. At present, commercial high frequency array systems are not yet available at frequencies above 50 MHz mainly due to limitations in fabricating of hundreds or even thousands small-scale elements, electrical interconnections, and system development. However, annular array transducers for high frequency ultrasonic imaging can bridge the gap between single-element transducers and linear/2-D array transducers, which can be dynamically focused, yielding better image quality than fixed focus single-element transducers. Compared to linear/2-D arrays, annular arrays have fewer elements which simplify the fabrication and require less complex electrical systems. The drawback is that mechanical scanning is still needed. Several researchers have developed high frequency annular arrays. Brown et al. [1], fabricated a kerfless array by patterning aluminum electrodes on a planar PZT-5H substrate. Ketterling et al. [2] developed a 40-MHz annular array transducer using PVDF material, whereas Gottlieb et al. [3], used P(VDF-TrFE) film and a double sided flex circuit to fabricate a similar transducer. These piezoelectric polymer based kerfless arrays in general tend to have a low sensitivity due to its low clamped dielectric constant and k_t values, which may be better suited for fabricating transducers at lower frequencies or with large aperture sizes. Kerfless PZT array suffers high cross talks between adjacent elements.

Piezoelectric composite materials have many attractive characteristics for ultrasonic transducer applications, especially for array transducers. PMN-PT/epoxy 1–3 composites offer a large number of design parameters, including the PMN-PT pillar dimension, epoxy selection, and volume fraction of PMN-PT, which can be easily tuned to optimize composite material performance for a certain application. Firstly, for 1–3 composite material, piezoelectric pillars may be embedded in soft epoxy matrices, thus minimizing lateral clamping between active piezoelectric elements. As a result, a higher electromechanical coupling coefficient for the composite can be obtained than that of the bulk material operating in a plate mode [4]. PMN-PT single crystals have the highest pillar mode piezoelectric properties (k_{33} over 0.90). Furthermore, this special structure can significantly decrease inter-element crosstalk, which is very critical for the high frequency array transducer with small elements. Secondly, with the addition of epoxy, the effective acoustic impedance of the composite is much lower (∼18 MRayls) than that of

* Corresponding author. Tel.: +1 213 821 2651.
E-mail address: cliu@geospace-research.com (C. Liu).

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single crystal PMN-PT (∼30 MRayls). This facilitates better acoustic impedance matching between the transducer and human tissue, which results in improved energy transmitting and receiving. Thirdly, the shape and layout of piezoelectric pillars can be adjusted to avoid spurious resonances generated in periodic composites. As a result, wider bandwidths can be obtained; hence axial resolution can be improved.

The two greatest challenges in developing high frequency ultrasonic arrays are: (1) fabricating elements that are very small and (2) the construction of an electrical interconnection system for array elements with narrow pitches. These problems also exist in the fabrication of high frequency annular arrays, although they are alleviated to a certain extent because of the comparatively smaller number of elements. Nevertheless new methodologies are required for the development of high frequency annular arrays. Fabrication of PMN-PT composite for high frequency arrays requires that the pillars/kerfs have very small dimensions. For example, at 70 MHz, the pillar size should be less than 10 μm. For the current study a kerf width of ∼5 μm was selected. The traditional dicing-and-filling method [5,6] and other precise machining methods, such as laser ablation [7], cannot accomplish the task. Based on interdigital pair bonding techniques [6], Chabok et al. [8] developed a 35 MHz PZT 1–3 composite annular array transducer using dicing technology. Microfabrication techniques [9] and MEMS technologies [10] on the other hand offer an easier alternative for the production of PMN-PT composite materials and development of high frequency ultrasonic arrays. However, till now there are no such efforts in developing high frequency array transducers using micromachining techniques.

For high-frequency arrays, electrical connection to each element is preferentially made on the back side of the transducer, which simplifies the top surface topology. Current electric interconnection methods for array transducers include wire bonding [1], flex circuits [2], and multi-layer thick film circuits [11]. With the wire bonding method, fine metal wires must be bonded onto each element; this limits the utility of the process to larger number of elements. Flex circuits or multi-layer circuits are directly attached to the array elements to expand electrical connections. The backing material is then added on the circuits. They are widely used in low frequency array transducers. However, acoustic impedance mismatching between flex circuits and the backing material sometimes cannot be tolerated by high frequency ultrasound transducers. A better and often used approach for high-frequency transducer design is to directly attach the piezoelectric element to a conductive backing material [12]. Poor adhesion to the backing material and wire connection may cause long ringing in the pulse echo waveform, which has been observed by [10]. Thus, a better electrical connection method needs to be explored.

In this paper, a first attempt in utilizing micromachining and Micro-Electro-Mechanical System (MEMS) technologies to fabricate high-frequency ultrasonic annular array transducers is reported. PMN-PT/epoxy 1–3 composite was produced by micromachining processes, combining photolithography and dry etching techniques. A conductive backing material was directly attached to each array element and separated by an insulating mold. In addition, a new electric connection strategy was implemented that could be applied to many types of array transducers with fine elements and narrow pitches.

2. Array design

A common design for annular arrays entails making the area of each element equal. The array discussed here had an aperture diameter of approximately 1.3 mm with six equal area (0.2 mm^2) elements separated by 16-μm kerfs. The radius of the center circle element r_1 was 250 μm. The outer radii of the other five annuli were calculated using the following equation:

$$r_i = \sqrt{r_1^2 + (r_{i-1} + kerf)^2}, \quad (i = 2, 3, \ldots, 6) \quad (1)$$

where *kerf* represents the spacing between elements. The desired central frequency was 50 MHz. The kerf between elements was a constant value of 16 μm. The effective inner and outer radii for each element were listed in Table 1.

Table 1
Geometry for annular array.

Element no.	Inner radius (μm)	Outer radius (μm)	Width (μm)
1	0	250	250
2	266	365	99
3	381	456	75
4	472	534	62
5	550	604	54
6	620	668	48

PMN-PT/epoxy 1–3 composite with a PMN-PT volume fraction of about 50% was used. Composite piezoelectric materials have many advantages as mentioned above. However, there are lateral resonance modes between periodically placed pillars of the composite, which limit the highest working frequency of the material. In this work, a random layout of the pillars was used to avoid periodic arrangements. All pillars were laid out concentrically with no parallel edges, and the distance between each pillar was not exactly the same. This kind design restricted spurious resonance modes in the composite and at the same time improved bandwidth. The kerf width of the composites averaged about 6 μm and the dimension of the pillars was 9 μm by 9 μm.

To predict the performance of the annular array, a series of simulations using Field-II [13] and PiezoCAD (Sonic Concepts, Inc., Bothell, Washington) were carried out, which is similar to [14]. Table 2 summarized some key design parameters, material selection, and simulation results for the array transducer. With 8 μm-thick parylene as a matching layer and E-solder as the backing material, the central frequency of the array transducer was 51 MHz and the −6 dB bandwidth 88%.

Table 2
Design parameters, material selection, and simulation results of annular array.

Piezoelectric material	50% Volume fraction PMN-PT composite
Thickness	25 μm
Number of elements	6
Area of each element	0.25 mm^2
Matching layer	8 μm Parylene
Backing material	E-solder
Central frequency	51 MHz
−6 dB Bandwidth	88%
−6 dB Pulse width	16 ns

3. Array fabrication

3.1. PMN-PT 1–3 composite and transducer stack

In our current design, the PMN-PT/epoxy 1–3 composite was produced using microfabrication processes, combining photolithography and dry etching techniques. This has several advantages, such as batch processing, submicron machining precision, and low cost for mass production. Fig. 1 illustrates the process flow for PMN-PT/epoxy 1–3 composite fabrication.

A single crystal PMN-PT plate (H C Materials, Bolingbrook, IL) with dimensions of 25 mm by 12 mm and 0.65 mm thickness was lapped on both surfaces down to a thickness of 0.5 mm and