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Short communication

# Implementation of a PMN-PT piezocrystal-based focused array with geodesic faceted structure

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ABSTRACT

The higher performance of relaxor-based piezocrystals compared with piezoceramics is now well established, notably including improved gain-bandwidth product, and these materials have been adopted widely for biomedical ultrasound imaging. However, their use in other applications, for example as a source of focused ultrasound for targeted drug delivery, is hindered in several ways. One of the issues, which we consider here, is in shaping the material into the spherical geometries used widely in focused ultrasound. Unlike isotropic unpoled piezoceramics that can be shaped into a monolithic bowl then poled through the thickness, the anisotropic structure of piezocrystals make it impossible to machine the bulk crystalline material into a bowl without sacrificing performance. Instead, we report a novel faceted array, inspired by the geodesic dome structure in architecture, which utilizes flat piezocrystal material and maximizes fill factor. Aided by 3D printing, a prototype with f# ≈ 1.2, containing 96 individually addressable elements was manufactured using 1–3 connectivity PMN-PT piezocrystal–epoxy composite. The fabrication process is presented and the array was connected to a 32-channel controller to shape and steer the beam for preliminary performance demonstration. At an operating frequency of 1 MHz, a focusing gain around 30 was achieved and the side lobe intensities were all at levels below −12 dB compared to main beam. We conclude that, by taking advantage of contemporary fabrication techniques and driving instrumentation, the geodesic array configuration is suitable for focused ultrasound devices made with piezocrystal.



## 1. Introduction

The use of focused ultrasound as a means to deliver energy has been expanding since the 1990s in areas including high intensity focused ultrasound surgery (FUS) [1], ultrasound-mediated targeted drug delivery (UmTDD) [2] and particle trapping and manipulation [3]. The focused ultrasound beam can be achieved geometrically with a curved piezoelectric bowl or acoustic lens or electrically with a multi-element phased array. The combination of both approaches is also common, with many arrays with overall concave geometry for focusing used in research and clinical practice [4–6]. This is because concave arrays can provide higher focal intensities than planar arrays with similar overall dimensions. Furthermore, when only a limited range of movement in the focal point is necessary, fewer elements and simpler time delays are needed, reducing the complexity of the driving circuitry.

Historically, piezoceramics have been the most commonly used materials in ultrasound transducer arrays but, recently, the improved performance offered by relaxor-based piezocrystals in the $Pb(Mg_{1/3}Nb_{2/3})O_3$–$PbTiO_3$ (PMN-PT) family has been recognized. Piezocrystals are now used widely in biomedical ultrasound imaging and investigation of their possibilities is under way in nondestructive evaluation, particle manipulation and underwater sonar [7–10] based on piezoelectric properties including $k_{33} \approx 90\%$ and $d_{33} > 1500$ pC/N [11]. Bulk, monolithic piezocrystal has little advantage over piezoceramic, with the values of $k_t$ being similar, but improved performance can be realized in configurations such as the planks used in biomedical imaging arrays and the pillars used in piezocomposites.

PMN-PT itself, termed a Generation I material, is susceptible to changes in functional properties at elevated temperature and pressure [12], but Generations II and III, respectively exemplified by ternary PIN-PMN-PT and doped ternary Mn:PIN-PMN-PT, are under development to reduce these effects whilst maintaining much of the performance advantage over piezoceramic, e.g. in terms of $k_{33}$ and $d_{33}$ that determine piezocomposite performance.

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Piezocrystal composites thus have potential to improve the effectiveness of focused ultrasound transducers and the work reported here contributes to this by describing the fabrication and testing of a 2D concave phased array made with Generation I piezocrystal.

A widely-reported method to fabricate concave transducer arrays is to place individual single-element transducers in a prefabricated frame at predetermined positions [6,13]. This requires manufacture of each individual array element separately and the presence of the frame can significantly reduce the array fill-factor, i.e. the percentage surface coverage of the active piezoelectric material, and thus the focusing gain and acoustic energy output of the transducer. As an alternative, Raju et al. [14] proposed an array design using a spherically-focused ceramic bowl with printed electrodes defining the elements. However, fabrication of curved sections from piezocrystal boules would be wasteful of material which costs $\$0.5-3/\text{mm}^3$, and more importantly, performance would be decreased by the lack of alignment between the piezocrystal axes and the surface of the array. Mechanical forming to focus piezocrystal transducers has been achieved successfully using mechanical hard-press [15] and dimpling techniques [16], but reports are limited to single-element transducers. Other possibilities are to thermally form a 1–3 connectivity piezoelectric - polymer composite into the desired shape [17] or to use flexible polymers for flexible composites [18], but these may be difficult at the frequencies of interest here, below 1.0 MHz, and the values of volume fraction, e.g. $VF > 50\%$, used in focused ultrasound applications.

In this short communication, a novel array structure is described to utilize 1–3 connectivity piezocrystal–polymer composites in a geometrically focused array transducer. The practical challenges associated with the fabrication of the array structure and electrical interconnects to the elements are addressed. 3D printing is introduced to aid assembly. The performance of the array is demonstrated and its use with a 32-channel modular array controller is described, illustrating both beam shaping and the relocation of the focus required in focused ultrasound applications.

## 2. Geodesic structure

The faceted spherical structure proposed in this work is drawn from the architectural design of geodesic domes. These domes comprise multiple triangles approximately equal in size, with their vertices lying on the surface of a sphere. The planes of the triangles lie physically inside the sphere but the structure approximates a sphere whilst maximizing the coverage of the aperture with the piezoelectric material.

A section of an icosahedron dome structure with dome frequency *6V*, referring to a structure with six subdivisions of the original triangles in one icosahedron [19], was chosen for the proposed array. In total, the section requires 24 triangular flat plates positioned as shown in Fig. 1. To match a commercial piezoelectric bowl used as a reference, the target operating frequency of the array was 1.0 MHz and its aperture was 62 mm across its largest diagonal, with a natural focal distance of 75 mm, equal to the dome radius, giving f# ≈ 1.2. Table 1 lists the four triangular geometries in this design, with their side lengths and corresponding angles. Each triangle is named for its sides taken in a clockwise direction. Five side lengths in total are needed, denoted D, F, G, H and I. Triangles HGG and HII are isosceles and triangles DFG and DGF are scalene; six of each type are required. These triangles were machined by a precision dicing saw (MicroAce 66, Loadpoint Ltd., Wiltshire, UK) with dicing position accuracy of 0.001 mm and theta axis resolution of 0.0005°.

To increase the number of array elements for more flexible control over beam forming, each triangular plate was sub-divided into four smaller triangular elements by dicing along the mid-segments of the plates to half their thickness. The number of individual transducer elements was thus increased from 24 to 96, as shown in Fig. 1c, with only one additional step in the fabrication process. Each sub-diced element is connected to an individual signal wire at the rear and a common silver ink electrode ground with a single wire at the front.

## 3. Piezomaterials

The geodesic faceted structure was realized with two different piezoelectric materials: bulk ceramic to test the fabrication process and geodesic geometry and 1–3 connectivity PMN-PT piezocrystal–epoxy composite for performance evaluation. As noted previously, 1–3 composite is necessary to take advantage of the high values of $k_{33}$ and $d_{33}$ of PMN-PT.

For initial evaluation of fabrication, a pre-electroded piezoceramic plate, thickness 2 mm for 1 MHz operational frequency, (PZ26, Meggitt Sensor Systems, Kvistgaard, Denmark) was diced and separated into 24 triangular plates and then sub-diced into 96 sub-elements with 210 μm kerf width and 1 mm depth. Similarly, another set of 24 triangular plates was diced from 1–3 connectivity PMN-29% PT (Sinoceramic Inc., Shanghai, China) – hard polymer (Epofix, Struers A/S, Ballerup, Denmark) piezocomposite fabricated in house using the dice-and-fill method. Epofix was chosen for its low shrinkage, mechanical strength, low Poisson's ratio, and chemical resistance [20]. The piezocomposite material had a dicing kerf of 113 μm, a volume fraction, $VF = 60\%$, and a pillar aspect ratio (width to thickness), $PAR = 0.32$. It was lapped to a thickness of 1.2 ± 0.02 mm to achieve the 1.0 MHz operational frequency. Electrodes were applied on both sides of the triangular piezocomposite plates using silver ink (118-09A/B, Creative Materials Incorporated, USA) cured at 65 °C for 16 h. One electrode face on each triangular piezocomposite plate was part-diced into four smaller triangular divisions, while the ground electrodes on the opposite faces were left intact.

## 4. Array assembly

The process to assemble the array transducer from the machined triangular plates is illustrated in Fig. 2, with a corresponding photograph for each step.

An important aspect of this process is the placement of each triangular plate in the position needed to create the 3D faceted structure. The target wavelength, $\lambda \approx 1.5$ mm, indicates the need for precision much better than 1 mm. Hence, an ABS thermoplastic mould with faceted surfaces matching the geodesic design was made by 3D printing (uPrint SE 3D Printer, Stratasys Ltd, USA), as seen in Fig. 2a and c. The layer resolution of the 3D printer was 0.254 mm. Honey thinned in a small container in a warm water bath at 50 °C was used to hold the plates in place, providing lower viscosity compared to other temporary adhesive options such as silicon grease and thus minimizing the layer thickness on the mould (Fig. 2b). The use of honey also allows the mould to be released and the residue to be removed with water. The triangular composite plates were placed on the mould in the arrangement indicated in Fig. 1b and secured with 5 min-curing epoxy (Araldite® Rapid, Huntsman Advanced Materials GmbH, Switzerland), (Fig. 2d and e).

Because of the thermal sensitivity of PMN-PT piezocrystal, with rhombohedral to tetragonal phase transition temperature, $T_{RT} \approx 80$ °C [21], conductive silver epoxy (G3349, Agar Scientific, UK) rather than soldering was used for the electric connections. Silver ink was also discarded as an option as its viscosity is much lower than that of silver epoxy and it does not have the physical integrity