2-D Crossed-electrode Transducer Arrays for Ultrasonic Particle Manipulation

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***Abstract*— This paper reports research into the use of a crossed-electrode two-dimensional thick film lead zirconate titanate ultrasonic transducer array for particle manipulation under the control of electronics based on field programmable gate arrays. The array consists of 30 × 30 transducer elements defined by electrode crosspoints and works at approximately 7.25 MHz. Laser vibrometry of the array surface displacement profile demonstrates that single or multiple elements can be addressed and multiplexed with bespoke electronics. The array has also been demonstrated for particle manipulation with planar resonators. The results suggest potential to create dexterous acoustic tweezing devices with reconfigurable electronics and batch-produced screen-printed ultrasound transducer arrays with large number of elements.**

Keywords—crossed-electrode; thick film; FPGA; ternary switching; multiplexing; particle manipulation

I. Introduction

Microparticle manipulation with ultrasonic transducers, termed acoustic tweezing, has gained interest in recent years as it offers a contactless approach to handle particles without the need for sample pre-treatment. Extensively used in medical imaging, ultrasound arrays have been recently adopted in acoustic tweezing because large numbers of array elements offer improvements in tweezing dexterity. Microparticles can be concentrated at pressure nodes or anti-nodes and manipulated in two dimensions (2-D) with array-based planar resonators [1] or counter-propagating wave devices [2] by switching the active elements, or changing the phases of the driving signals. 3-D acoustic manipulation has also been demonstrated with complex holographic fields created by 2-D matrix arrays [3].

Although implementation of 2-D arrays can greatly increase dexterity in microparticle manipulation, a challenge remains in fabrication of miniature arrays with conventional machining and packaging techniques. As the number of elements increases, the electrical interconnection becomes more difficult. Reliable driving and control electronics are also required for specific applications. The authors have previously demonstrated that 2-D matrix arrays made with thick film PZT have significant advantages in simplifying the fabrication process and allowing for integration of miniature electronics [4].

This paper explores the feasibility of developing thick film 2-D arrays with the crossed-electrode configuration, also called row-column addressing. Individual piezoelectric elements can be defined by the intersecting areas of electrodes patterned orthogonally on the top and bottom of the piezoelectric material. Large number of elements can be achieved, with the number of electrical interconnections reduced by one or two orders of magnitude compared with conventional matrix arrays. Bespoke electronics based on field-programmable gate arrays (FPGAs) can also developed for driving the array in particle manipulation applications.

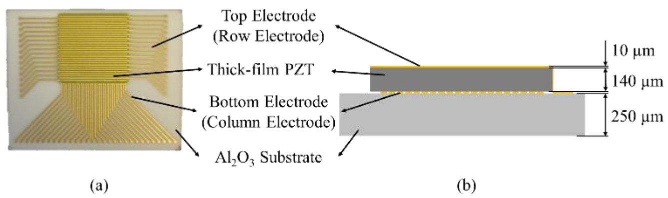

Fig. 1. 2-D crossed-electrode array made with a screen-printing process. (a) Top-view photograph of the array. (b) Cross-sectional diagram of the layers in the device and the thickness of each layer.

II. Ultrasound Transducer Array Development

A. *Screen-printed Transducer Array*

The crossed-electrode array described here was fabricated from thick film PZT (IKTS-PZ5100 [5], Fraunhofer IKTS, Germany) using a screen-printing process reported elsewhere [4]. A 140-µm-thick 15 mm × 15 mm piezoelectric layer was printed and sintered on a 250-µm-thick 100 mm × 100 mm alumina substrate (99.6%, Rubalit 710, CeramTec AG, Germany). The top and bottom electrodes of the PZT were made from Au-based electrode paste (C5789, Heraeus, Japan), and patterned orthogonally with printing on both sides. The electrode pitch is 500 µm, with a 60 µm kerf. The device has 30 top (row) electrodes and 30 bottom (column) electrodes and is thus able to address 900 cross-point array elements (Fig. 1). The electrode fan-outs have standard 1.27 mm (0.05 inch) pitch for ease of electronics integration.

B. *Functional Modelling*

Finite element (FE) modelling, using PZFlex (Weidlinger Associates Ltd, Glasgow, UK), was implemented to predict the array performance. The modeling was conducted with material properties reported previously by the authors [4].

The simulation was performed for a quarter of the array, and 3-D modelling of different top - bottom electrode actuation patterns were performed to examine the mode-shapes of the array. The excitation signal used in the models was a half cycle sinusoid at 15 MHz, and the models were allowed to decay fully within the runtime. Symmetry boundary conditions were assigned at the minima of the *X* and *Y* axes and free boundary conditions were assigned on the other sides to represent air. Three different electrode activation configurations were tested (Fig. 2): one column of elements, a single element and four elements. Models confirmed array functionality, especially for the cases of single-element and multi-element activation, with mode shapes indicating significant vibration of the active areas. Vibrations with lower amplitude also appeared over adjacent inactive elements. This is mainly because, as a kerfless 2-D array, the vibration is coupled laterally along the PZT thick film and substrate, from the active elements to the surrounding area.

III. Electronics Development

Conventional piezoelectric transducer arrays are usually constructed with separate active electrodes on one side of the piezoelectric elements and a common ground electrode on the other side. Individual elements can be addressed via a binary signal switching method, by connecting the active electrodes to either an AC signal source or ground to define "on" and "off" status of the transducer elements, respectively. The authors have demonstrated the possibility to perform array element multiplexing with analogue switch integrated circuits (ICs) under the control of FPGA electronics [6]. For a crossed-electrode array, it is also possible to address individual elements with the same electronic hardware, with different element switching approaches. In this paper, single-pole-double-throw (SPDT) analogue switches (ADG5434, Analog Devices, Inc., Norwood, MA, USA) are used for AC signal multiplexing, and a FPGA (XC3S700A, Xilinx, Inc., San Jose, CA, USA) is used as the digital control.

Because there is no common ground electrode in the crossed-electrode array, a ternary electrical switching scheme is needed to address a single element without interfering with surrounding electrodes. This switching is realized by using "signal", "ground" and "high impedance" states to control the top and bottom electrodes. Through an array of analogue switch ICs, the top electrodes are toggled between the signal and high-impedance states, and the bottom electrodes are toggled between the ground and high-impedance states (Fig. 3). Hence, for each element defined by the intersectional area of a top-bottom electrode pair, there are 2 × 2 combinations in total, represent one "on" status and three "off" statuses. Considering the small on-resistance, R_{on} = 13.5 Ω typical, introduced by the selected analogue switch, the "on" status creates a high current path for the AC signal to drive the transducer. Two of the "off" statuses are simply realized by supplying no driving signal to either electrode. For the third "off" status, a relatively high impedance component, R_{high} = 1 MΩ, is connected in the electrical path to limit the current flowing through the transducer, in turn to reduce the voltage across the transducer electrodes close to zero.

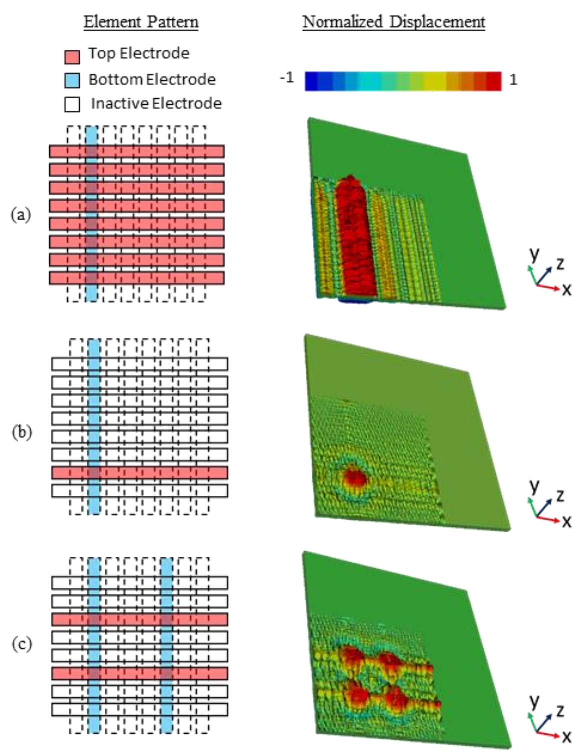

Fig. 2. PZFlex simulation results of crossed-electrode arrays with different activation patterns: (a) one column of elements, (b) single element, (c) four elements.

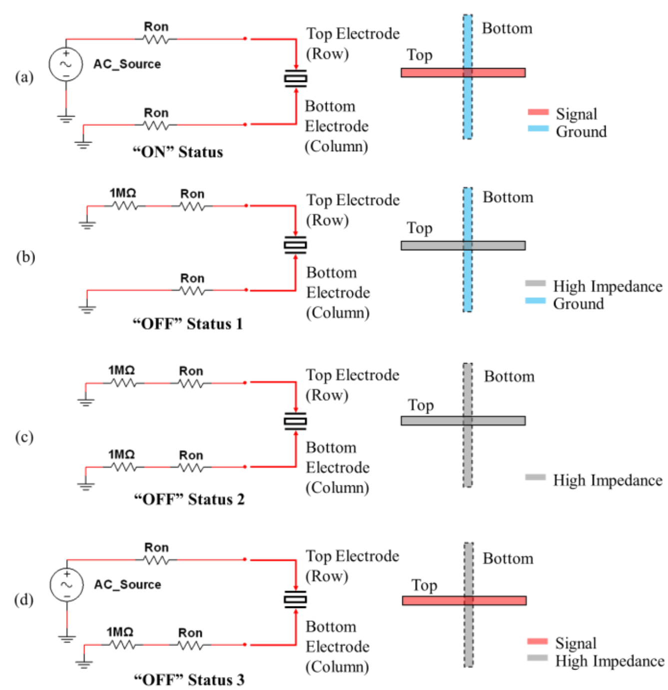

Fig. 3. Illustration of ternary configuration for driving a crossed-electrode array with equivalent circuits and electrode arrangements for the "on and "off" statuses. (a) "On" status for the active element. (b) – (d) "Off" statuses for the inactive element.

The analogue switches for the top and bottom electrodes are integrated into a single printed circuit board (PCB) as a multichannel signal switching circuit. The active driving signal is provided by an external function generator (33250A, Keysight Technologies Inc., Santa Rosa, CA, USA). Each electrode is controlled individually through the logic design in the FPGA. Different element activation patterns can be realized by editing the contents of the FPGA memory that determine the top-bottom electrode combinations. The activated elements can also be multiplexed through the entire 2-D array by using control logic to interpret commands provided from external hardware such as push-button inputs and to trigger the successive logic to control the analogue switches.

IV. System Characterization

Since the crossed-electrode array has a symmetrical structure, an area of 8 × 8 transducer elements located at the corner of the array was characterized, under the control of the bespoke FPGA-based electronics. The array was bonded onto a PCB frame with electrical connections from the array electrode to the standard header pins to connect the control electronics.

A. Impedance Spectroscopy

The impedance spectrum of each transducer element defined by a top-bottom electrode pair was measured with an impedance analyzer (4395A, Keysight Technologies Inc., Santa Rosa, CA, USA). The electrical impedance characteristics across all the elements have good consistency. For each element, the first thickness-extensional resonance frequency of the PZT and the Al_2O_3 layer together is found around 7.25 MHz, with an electrical impedance magnitude of 40 – 50 Ω.

B. Electronics Characterization

The fabricated analogue signal switching circuit has a -6 dB bandwidth of 20 MHz. At the array working frequency around 7 MHz, the channel crosstalk is as low as -30 dB. With a 50 Ω output load, each channel is able to provide AC signals with voltages up to 24 V_{pp} and peak current of 120 mA.

C. Laser Vibrometry

The surface displacement profiles for different element activation patterns of the array were measured with a laser vibrometer (OFV-534 / OFV-2570, Polytech GmbH, Waldbronn, Germany) with an associated 2-D translation stage. The laser beam generated from the optical sensor is focused with a 10 × microscope objective to give a laser spot size of around 400 µm diameter. During the scan, the array elements were activated with a continuous sinusoidal signal from the function generator, under the control of the signal switching circuit. 8 × 8 elements cover an area of 3.94 mm × 3.94 mm, hence the laser scanning was performed over a larger area of 6 mm × 6 mm, with 0.1 mm step resolution.

The array elements were activated at 7.25 MHz, in different patterns comprising one row of elements, one column of elements, a single element and multiple elements (Fig. 4). Because the equivalent electrical impedance varied in the different cases, the driving voltages changed accordingly. The displacement mapping results of different activation patterns

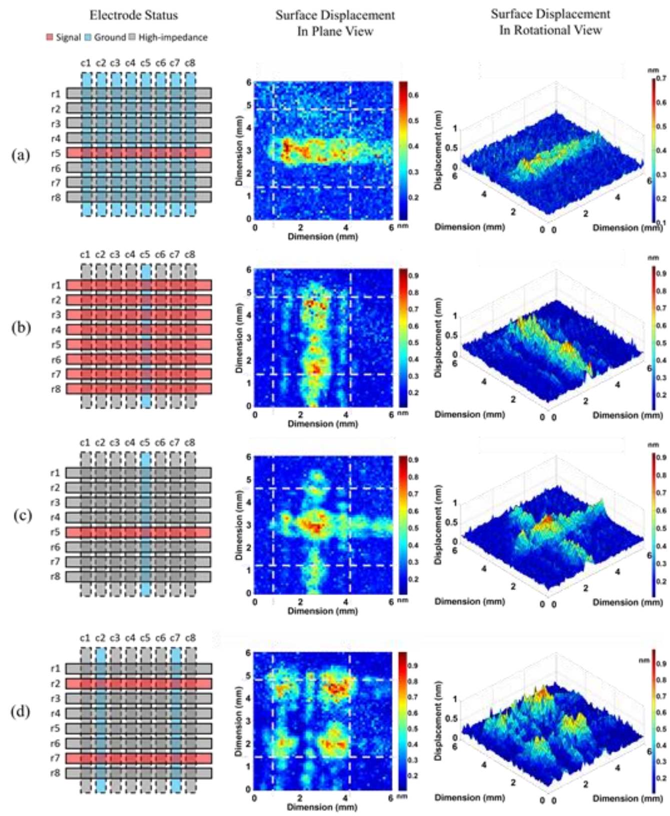

Fig. 4. Surface displacement measurements of array elements in different activation patterns. (a) Activation of Row 5. (b) Activation of Column 5. (c) Activation of an element defined by Row 5 and Column 5. (d) Activation of four elements defined by Row 2, Column 2, Row 7, and Column 7.

show good agreement with the FE simulation, as well as the realistic localization of the elements.

For different activation patterns, the driving voltages, maximum displacement and element dimensions of the active elements are summarized in Table 1. The dimensions of the elements are measured at positions corresponding with -3 dB of the maximum displacement amplitude. The overall effective area of the 8 × 8 elements is measured as 3.5 mm × 3.5 mm. A single line of elements was activated along every row or column. Single element activation was tested across the array from combinations of Row 1, Column 1 to Row 8, Column 8. Four elements with shared electrodes were also activated for the test, from the array corners along the diagonals to the center.

V. Experimental Demonstration

The functionality of the crossed-electrode array for particle manipulation was tested with planar resonators [1], [4]. A 6 mm wide, 300 µm thickness glass capillary (VitroCom, Mountain Lakes, NJ, USA) was used as a fluid chamber to levitate and concentrate microparticles. The capillary was coupled to the alumina side of the array with ultrasound gel. 10 µm diameter fluorescent polystyrene particles (Fluoresbrite, Polysciences, Inc., Warrington, PA, USA) mixed with water were introduced into the capillary.

In the experiment, a single element, located at Row 5 and Column 8 (r5c8) was activated initially. With the addition of the

TABLE I. SUMMARY OF LASER VIBROMETRY MEASUREMENTS

Activation Pattern	Driving Voltage (V_{pp})	Maximum Displacement (nm)	Element Dimension (mm)
Row	9.2 ± 0.2	0.91 ± 0.32	0.6 ± 0.2
Column	8.0 ± 0.7	0.96 ± 0.04	0.5 ± 0.1
Single element	12.4 ± 0.8	1.03 ± 0.11	0.6 ± 0.2
Four elements	12.0 ± 0.7	1.03 ± 0.17	0.5 ± 0.1

water-filled glass capillary, the device resonant frequency increased to 7.29 MHz. Particles were concentrated together into an agglomerate with a diameter of approximately 650 μm above the intersection r5c8. The activation was then shifted by one element along either a row or column. As shown in Fig. 5, the agglomerate was moved by the equivalent distance by the acoustic force introduced from the variation of the kinetic energy gradient in the standing wave field [1]. Such acoustic forces were balanced with Stokes drag forces. The agglomerate was manipulated at a speed of around 370 μm/s in the row direction and 810 μm/s in column direction, with corresponding forces calculated as 2.3 nN and 5.0 nN, respectively.

VI. CONCLUSION AND FUTURE WORK

A. Conclusion

This paper has demonstrated the feasibility of using screen-printed 2-D crossed-electrode transducer arrays for ultrasonic particle manipulation. With bespoke electronics constructed from analogue switches, array elements defined by the cross-sections of row and column electrodes can be individually addressed. Single or multiple active elements can be easily multiplexed for particle manipulation, under the control of re-programmable electronic devices such as FPGAs. This research demonstrates the possibility to build low-cost 2-D transducer arrays with a large number of elements with simplified electrical interconnections.

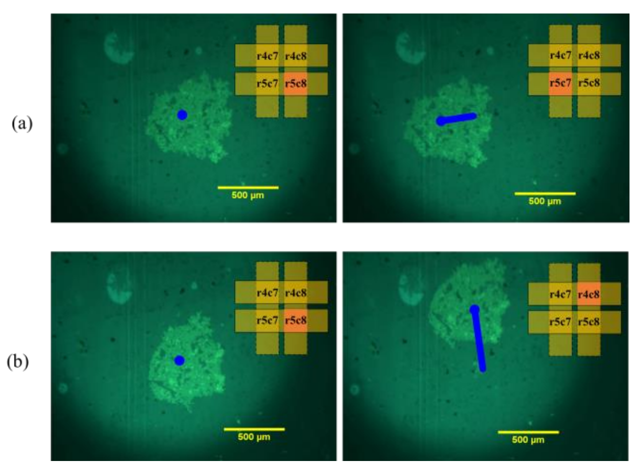

Fig. 5. Particle manipulation by one-element-step with crossed-electrode array. The agglomerate was shifted by (a) 268 μm in the row direction and (b) 487 μm in the column direction.

B. Future Work

The output current per channel provided from the analogue switches is limited if the number of active elements is increased, since the AC driving signal is provided from a single external source and multiplexed over the outputs. The fan-out capacity of the circuitry could be greatly increased by using separate ultrasound pulsers on all channels. Each output could then be configured independently through a logic device.

The current element addressing approach is able to activate and multiplex a single element or multiple elements with shared electrodes. However, it is also possible to activate multiple elements and manipulate each element independently by introducing time-sharing among the active elements, as shown in Fig. 6. Such a technique may also create arbitrary activation patterns with the array, which is potentially useful for developing re-configurable bioassays.

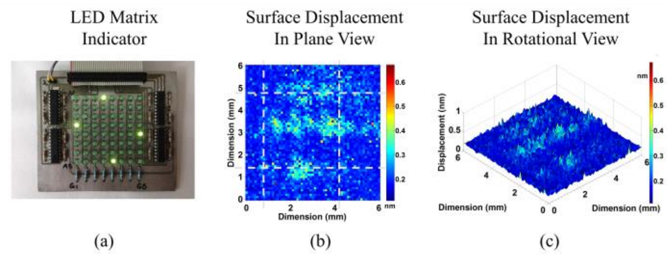

Fig. 6. Preliminary study to control multiple elements individually. Four array elements are addressed through time-shared activation with a sweep frequency of 250 Hz among the elements. Each element can also be manipulated independently. (a) The LED matrix is used to visualize the positions of the active elements. (b) and (c) Displacement mapping of the active elements.

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