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Performance and Crosstalk Evaluation of 2-D Array Piezoelectric Micromachined Ultrasonic Transducer with 3-D Finite Element Simulation

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***Abstract*— Micro-machined ultrasonic transducer (MUT) arrays have their structure and fabrication technology fundamentally different to those of thickness mode piezoelectric transducers. Their performance needs to be modelled and optimized before MEMS fabrication process is engaged. A 3-dimentional finite element modeling (3-D FEM) analysis is established for the simulation of a 2-D 7×7 piezoelectric micro-machined ultrasonic transducer (PMUT) array in its cavity and buffer structure. The main characteristics and parameters of the PMUT are calculated in frequency domain, in terms of the electrical impedance, resonant modes patterns, stress distribution, and in particular the cross talk between array elements, The method provides an efficient tool for the design and optimization of PMUT structures. A novel structure with double active layers PMUT is proposed and simulated with the FEM.**

Keywords*— *PMUT array, FEM, crosstalk, optimization

I. Introduction

Ultrasonic array transducers have a pivotal role in acoustical imaging for medical diagnostic and nondestructive testing. The piezoelectric micromachined ultrasonic transducers (PMUTs) are concerned in recent years for their relatively easy process and high compatibility with semiconductor manufacturing process, allowing large-scale and high-density array fabrications. Furthermore, their integration with front-end modules minimizes ultrasound probes. With small size array elements, high working frequency transducers permit higher image resolution in phased array application, changing fundamentally the pattern of medical ultrasound imaging.

In the design and study of PMUTs, crosstalk between array elements is an important factor that has negative impact on the performance of beamforming, like reducing image resolution, producing artifacts in some severe cases. The crosstalk phenomenon in PMUT structures is essentially different from that in conventional bulk piezoelectric transducers. Capacitive micro-machined ultrasonic transducers (CMUTs) have similar structure to that of PMUTs [1-5]. In the investigation of CMUTs, some recent works [1,4] invoke wave phenomenon such as, Lamb waves, Sholte waves and Stonley waves which are responsible for crosstalk. However, as MUT array is usually periodical in structure, such type of waves cannot properly explain the dispersive property of communication between array elements. The energy transduction of PMUTs and CMUTs are both based on the vibration of a clamped membrane, but their wave excitation mechanism is quite different. In PMUTs, the membrane is driven by a deposited piezo-film while in CMUTs the vibration of the membrane is generated by dielectric force through a thin cavity. Due to structural differences, PMUTs' crosstalk mechanism has not been fully investigated [6-7].

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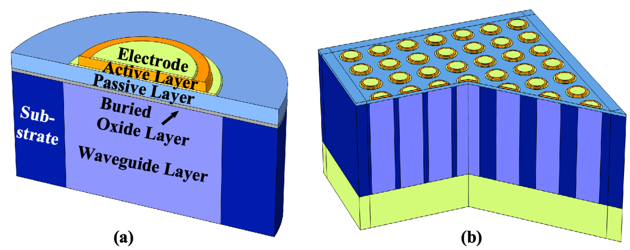

Fig. 1. 3-D schemetic of (a) designed PMUT cell, (b) modeled 7×7 PMUT array filled with PDMS and charged with water.

In this study a 3-D FE method (COMSOL) is set out, to investigate a 7×7 PMUT array. All main characteristics and parameters of the MUT, such as electrical impedance, the modes resonance, the stress distribution, and in particular the inter-elements crosstalk can be simulated. The calculation is performed in the frequency domain where the resonance behavior is analyzed. The crosstalk perturbation is quantified at each neighboring element by exiting a center element of the array. 3-D stress distribution can be visualized to help understanding the structural robustness. At last, a new structure with double active layers on either sides of the vibration membrane is proposed and studied for validating purpose.

II. Methodology

Fig. 1(a) shows the structure of the PMUT device. The actuation layer is a sandwiched AlN film of 1 μm in thickness deposited on a silicon passive layer (membrane), which is of 4

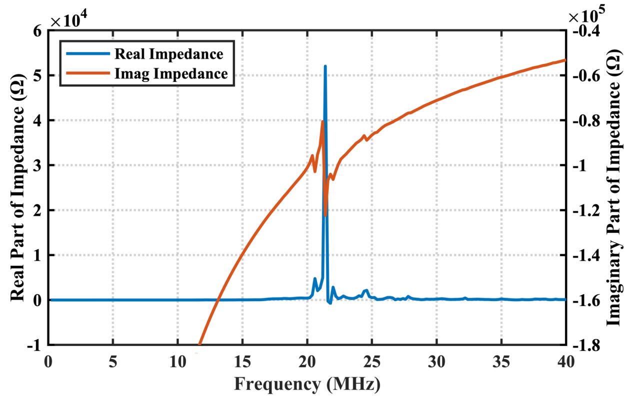

Fig. 2. Electrical impedacne response of the free-cavity PMUT array's center element, in real and imaginary parts.

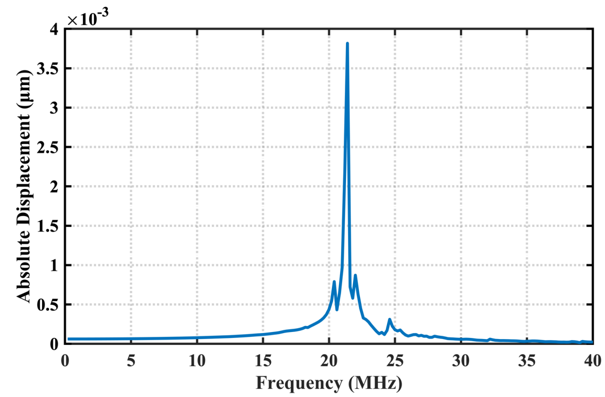

Fig. 3. Modulus of normal displacement response at the center of the free-cavity PMUT array's center element.

μm in thickness, and a SOI buried oxide layer of 300 nm in thickness. Electrodes are Molybdenum of 150 nm in thickness, providing ideal lattice match and electrical connections. Underneath the membrane is the supporting silicon substrate, with deep holes of 200 μm in thickness, filled with PDMS as wave buffer (waveguide). The whole array works at 20 MHz with a pitch spacing of 58 μm.

Two 3-D FE models are established for the 7×7 array, as shown in the Fig. 1(b). The first one corresponds to free vibration of the PMUT membrane array, i.e. without PDMS filling in the cavities. The boundaries of the cavities and the bottom of the substrate are set mechanically free. The four lateral faces of the array are set with perfectly matched layers (PMLs) to absorb wave energy. In the second model, the cavities are filled with PDMS. The PMUT is charged with water of 150 μm in thickness at the substrate bottom. The other extremity of the water layer is set as radiation boundary so that the wave transmitted into the water will be completely radiated without reflection. Due to the symmetry structure of the array and the transversely isotropic property of used materials, symmetry boundary conditions are used to save the 3-D FE simulation scale. This approach makes the calculation faster because the number of mesh elements can be reduced to 1/8 of the full device models. Another PMUT structure with double active layers on either sides of the silicon membrane is proposed (inset of Fig. 10), demonstrating the flexibility of FE method.

Frequency domain simulation are conducted for all these models in the range from 0.2 MHz to 40 MHz, and are subsequently post-processed/analyzed by MATLAB software, through a COMSOL interface — Livelink for MATLAB. The PMUT performance are evaluated in terms of the electrical impedance, stress distribution (in σ_{33} and σ_{11} components), vibration displacement pattern. The crosstalk is analyzed by potential response level of electrically open-circuit condition at all the neighbor elements when the center one is excited with a sinusoidal electric potential of 1 volt amplitude.

III. Results and Discusstion

A. Free-cavity PMUT array

The FE simulation is first carried out for the PMUT array under free cavity condition (without PDMS filling). The electrical impedance and the displacement response are

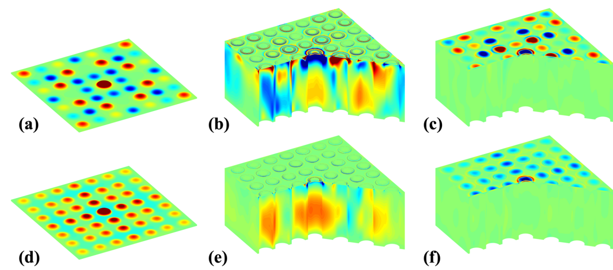

Fig. 4. Normal displacement and stress distribution of the free-cavity PMUT array: (a) displacement at 21.4 MHz, (b) σ_{33} stress component and (c) σ_{11} stress component at 21.4 MHz; (d) displacement at 24.6 MHz, (e) σ_{33} stress component and (f) σ_{11} stress component at 24.6 MHz.

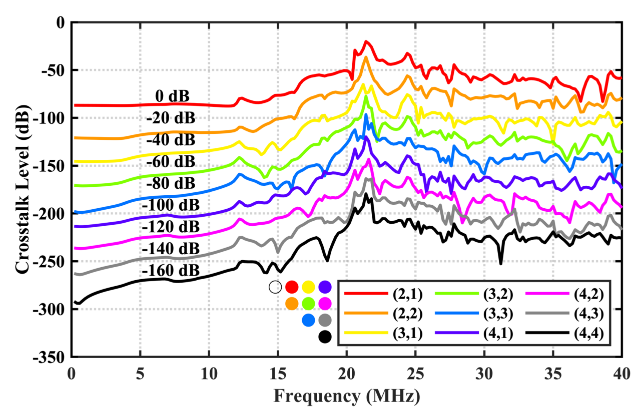

Fig. 5. Frequency reponse of the crosstalk for each element of the free-cavity PMUT array. From up to down, each element has an equal level difference by -20 dB and their relative positions to the center element are indicated by the xy-coordinates.

presented in Fig. 2 and Fig. 3 respectively, showing a principal resonant frequency of 21.4 MHz (the highest peak in the real impedance curve). The existence of several minor peaks can be explained by the periodicity of the PMUT array. At those minor peaks, there are wave propagation and communication between the array elements through the membrane, which are the origin of the crosstalk, while the wave reflection from the substrate bottom is rather the wave reverberation in the whole structure. Single array element model (theoretical or analytical) doesn't show the same perturbation, and there will be no such peaks if

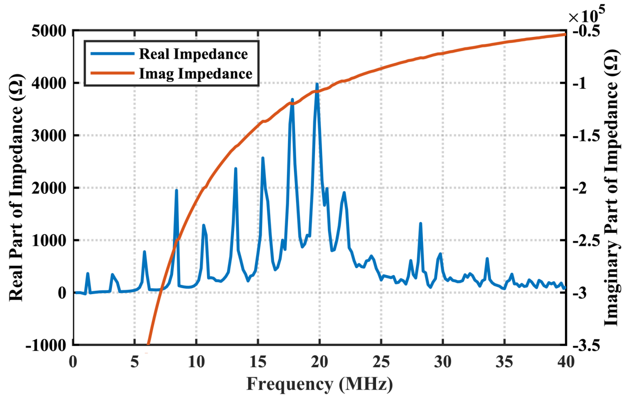

Fig. 6. Electrical impedacne response of the filled-and-charged PMUT array's center element, in real and imaginary parts.

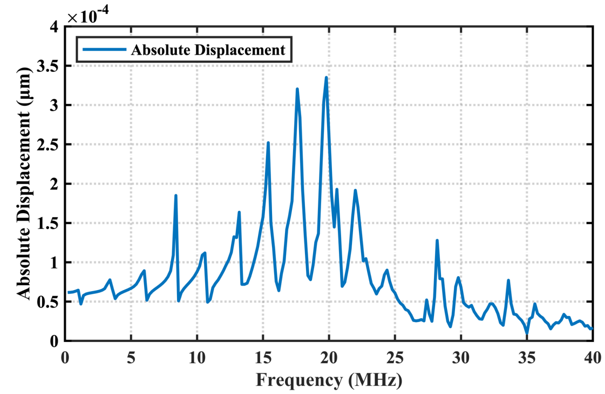

Fig. 7. Modulus of normal displacement response at the center of the filled-and-charged PMUT array's center element.

the element boundaries are set to wave absorption condition (PMLs).

To assess this crosstalk phenomenon, normal displacement at the PMUT surface and stress component σ_{33} and σ_{11} distribution in the membrane and in the substrate, given in their real part, are demonstrated in Fig. 4. The vibration of the center element is initialed as zero reference phase. The surface distribution (relative normal real displacement) at 21.4 MHz and 24.6 MHz show the resonance patterns at the center exciting element, as well as at the neighboring passive elements of which the vibration is induced by the crosstalk propagation. At the resonance frequency 21.4 MHz, the nearest neighbor elements have the opposite vibration phase and it alters for the elements receding from the center element (Fig. 4a). At the sub resonant peak of 24.6 MHz, all the elements vibrate in phase and the vibration amplitude decreases when their distance from the center one increases (Fig. 4d). Fig. 4c and Fig. 4f provide a perspective how crosstalk is propagated through the σ_{11} stress component.

The frequency response of the crosstalk for each element of the array is shown in Fig. 5. The highest crosstalk level is -16.57 dB at the first adjacent element (2, 2) along the diagonal line. Interestingly, the crosstalk on certain elements is significantly suppressed or enhanced, and their peaks are deviated or damped to some degree comparing themselves to the others. This can be attributed to their different geometry location within the array.

B. Filled-cavity (in PDMS) and Water-charged PMUT array

For real use of the PMUT array, the cavities are filled with PDMS, which serves as wave buffer and waveguide, and the PMUT is charged with a transmitting medium (usually water). The electrical impedance and the displacement response at the center of the excited center element in frequency domain are given in Fig. 6 and Fig. 7. Compared to the free cavity array, the main resonant frequency peak is slightly shifted to 19.8 MHz with an enlarged bandwidth, due to effect of the filling material. At this main resonance, a guided and partial standing wave is observed in σ_{33} stress component (Fig. 8b). Equally spaced peaks is presented in both the electrical impedance and the displacement response with a space interval of 2.56 MHz, which are the thickness resonance of the filling buffer layer (PDMS). The appearance of a sub peak at 28.2 MHz is the resonance of a radial mode in the cavity cylinder (cavity radius r = 24 μm),

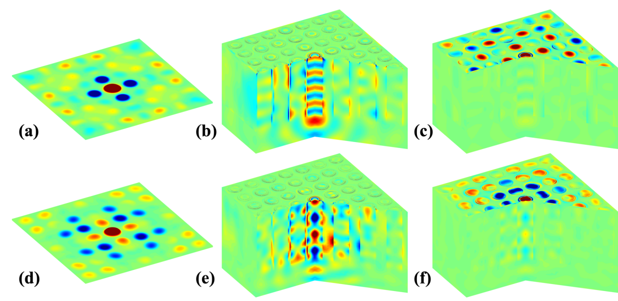

Fig. 8. Normal displacement and stress distribution of the free-cavity PMUT array: (a) displacement at 21.4 MHz, (b) σ_{33} stress component and (c) σ_{11} stress component at 21.4 MHz; (d) displacement at 24.6 MHz, (e) σ_{33} stress component and (f) σ_{11} stress component at 24.6 MHz.

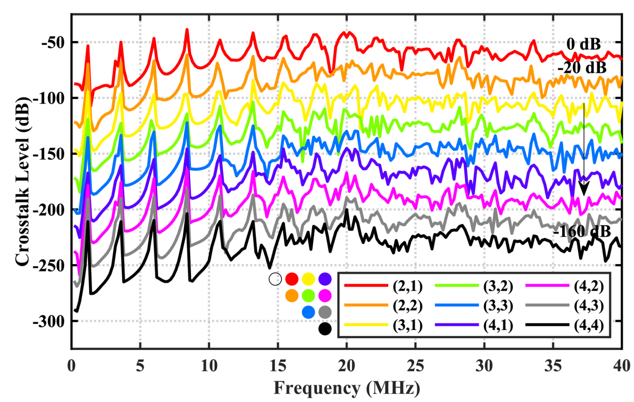

Fig. 9. Frequency reponse of the crosstalk for each element of the free-cavity PMUT array. From up to down, each element has an equal level difference by -20 dB and their relative positions to the center element are indicated by the xy-coordinates.

which can be confirmed by both the σ_{33} stress component distribution (Fig. 8e) and σ_{11} component (Fig. 8f).

Complete frequency response of the crosstalk for filled and charged PMUT array is shown in Fig. 9. The highest crosstalk level is -41.49 dB at the first adjacent element (2, 1) along the x-axis. Compared to the air-coupled PMUT array, the crosstalk of the filled PMUT array is significantly smaller because the excited wave energy is less concentrated in the membrane and is transmitted, then lost in the charging medium (water).

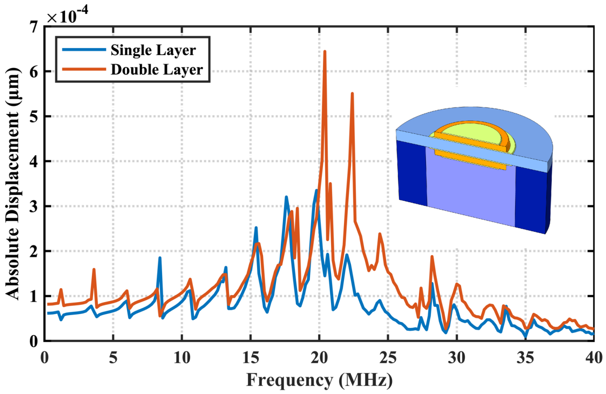

Fig. 10. Displacement comparison between the classical and the proposed dual-layer PMUT array, filled with PDMS and charged with water. Inset shows the 3-D schemetic of the proposed dual-layer PMUT cell.

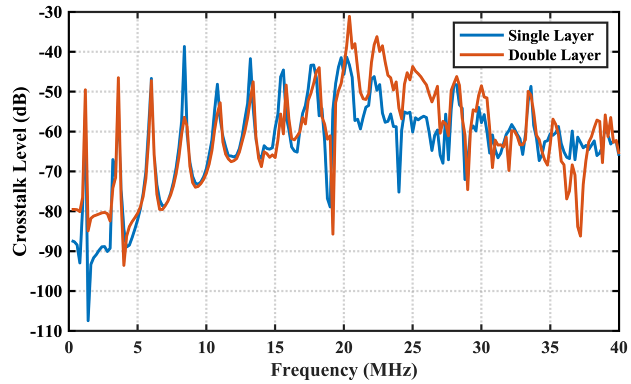

Fig. 11. Crosstalk level comparison between the nearest element of the classical and the proposed dual-layer PMUT array, filled with PDMS and charged with water.

C. *Dual-layer PMUT array*

For validation purposes, a newly proposed 7x7 dual-layer PMUT array (inset of Fig. 10) is simulated and evaluated using the FE method described above. As shown in the schematic, the PMUT cell is designed with two active layers on either side of the silicon membrane. In addition, the SOI buried oxide layer is removed in consideration of the manufacturing process.

In Fig. 10, there is a clear trend of increasing sensitivity at the slightly raised resonant frequency. Comparing dual-layer PMUT array with single-layer PMUT array (filled with PDMS and charged with water), the modulus of normal displacement at the center of dual-layer PMUT is almost doubled. Furthermore, higher structural rigidity cause resonant frequency to rise, so that absolute bandwidth is also increased.

Finally, the crosstalk response of the dual-layer PMUT array is compared to that of the single-layer PMUT array in Fig. 11. The highest crosstalk level of dual-layer PMUT array is -31.13 dB at 20.4 MHz. As the displacement of center of the array is higher, crosstalk response rises correspondingly. Thicker membrane could also contribute to the increasement of the crosstalk response, however not significantly.

IV. Conclusions

This study set out to evaluate the performance and crosstalk of a 2-D 7×7 PMUT array. By using 3-D FE method, three PMUT array models are analyzed providing multiple characteristics, including electrical impedance, resonance mode vibration pattern, stress distribution in the PMUT structure and crosstalk level response in frequency domain. This evaluating method exhibits high flexibility, provides a deeper insight into PMUT array design, analysis and optimization. The scope of this study was limited in terms of simulation topic, and more research is needed so as to explore the working mechanism of PMUT arrays.

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