ACOUSTIC CROSSTALK REDUCTION METHOD FOR CMUT ARRAYS

Baris Bayram, Goksen G. Yaralioglu[1], Mario Kupnik[1], and Butrus T. Khuri-Yakub[1]
[1]Edward L. Ginzton Laboratory, Stanford University, Stanford, CA 94305-4088

Abstract – **This paper reports on the finite element analysis (FEA) of crosstalk in capacitive micromachined ultrasonic transducer (CMUT) arrays. Finite element calculations using a commercial package (LS-DYNA) were performed for an immersed 1-D CMUT array operating in the conventional and collapsed modes. LS-DYNA was used to model the crosstalk in CMUT arrays under specific voltage bias and excitation conditions, and such a modeling is well worth the effort for special-purpose CMUT arrays for ultrasound applications such as medical imaging and high intensity focused ultrasound (HIFU) treatment.**

Compared to the existing finite element analysis (FEA) in literature, our FEA is distinguished by having all 5 main features together: First, the explicit, time domain solver of LS-DYNA enables the modeling of the actual CMUT array in detail, i.e. all 41 array elements are modeled. Second, user-defined subroutines provide an efficient electrostatic-structural coupling method. Third, the robust contact capability offers the CMUT modeling in collapsed operation. Fourth, a fast method to bias the CMUT array in conventional and collapsed modes is implemented. Fifth, the FEA results are verified with interferometer measurements.

Our finite element calculations show that the main crosstalk mechanism is the dispersive guided modes propagating in the fluid-solid interface. Conventional operation has a crosstalk level of -23 dB and the guided modes are not present above the cut-off frequency of 4 MHz. Most importantly, the crosstalk wave has a center frequency of 2.3 MHz with a narrow bandwidth although the transmitter element has a center frequency of 5.8 MHz with more than 130% fractional bandwidth. Crosstalk level is improved to -39 dB in collapsed operation, and the cut-off frequency becomes 10 MHz because of the contact between the membrane and the substrate. The Lamb wave modes have a crosstalk level around -43 dB in both operation modes. These finite element results show excellent agreement with the interferometer measurements of the fabricated CMUT array.

Using our verified FEA, we implemented a powerful method for the first time to reduce the crosstalk by impeding the propagation of the guided interface waves. This method is based on the acoustic band gap resulting from the periodic CMUT membranes on the fluid-solid interface. The crosstalk was effectively reduced by 10 dB down to -33 dB in the conventional operation without loss of acoustic pressure of the transmitter element. This method can be easily introduced into the fabrication of 1-D and 2-D CMUT arrays to achieve superior crosstalk.

I. INTRODUCTION

Ultrasound applications generally require transducer arrays composed of closely packed elements rather than single transducers for applications such as diagnostic imaging and high intensity focused ultrasound (HIFU). The close proximity of these neighboring elements in immersion applications generates the crosstalk, which degrades the overall performance of the array [1,2]. The purpose of this paper is to present the accurate modeling of the crosstalk in CMUT arrays in "linear" and nonlinear operation regimes [3-5] using time-domain, finite element method (FEM), and to reduce the crosstalk between array elements using this finite element model. Both the regular CMUT array used to verify the calculations with interferometer measurements and the modified CMUT array proposed to reduce the crosstalk are described. The FEM and the experimental results are compared for both conventional and collapsed operations in the frequency-wave number domain, and excellent agreement is observed. The main crosstalk mechanism is the dispersive guided modes propagating in the fluid-solid interface. The crosstalk in the regular and the modified CMUT arrays is compared in the time-spatial and the frequency-wave number domains, and the effectiveness of the modified CMUT array to reduce the crosstalk is presented.

II. FINITE ELEMENT CALCULATIONS

The 3-D finite element model of the 1-D CMUT array characterized in [6], includes approximately 1.7 million nodes [Fig. 1]. Because of the symmetry of the actual 41-element array around the center of the transmitter, only half of the array is included in the model. The symmetry along the length of each element allowed modeling half of the circular membranes.

ANSYS/LS-DYNA, a commercially available FEM package, was used to define the solid geometry, to mesh the structure, and to generate the final input deck for the LS-DYNA calculations.

The electrostatic-structural coupled forces within the electrodes are calculated using the user-defined loading feature of LS-DYNA [5,7]. The ideal contact elements (no friction, no binding forces) are defined on the top and bottom surfaces of the vacuum gap. The displacement data over the whole array was collected with a time step of 10 ns for a total time of 4 µs.

Regular CMUT arrays have a separation region between array elements [Fig. 2(a)]. Modified CMUT arrays include a membrane formed in the separation region [Fig. 2(b)]. Crosstalk reduction method based on this modification is evaluated using finite element analysis.

1051-0117/06/$20.00

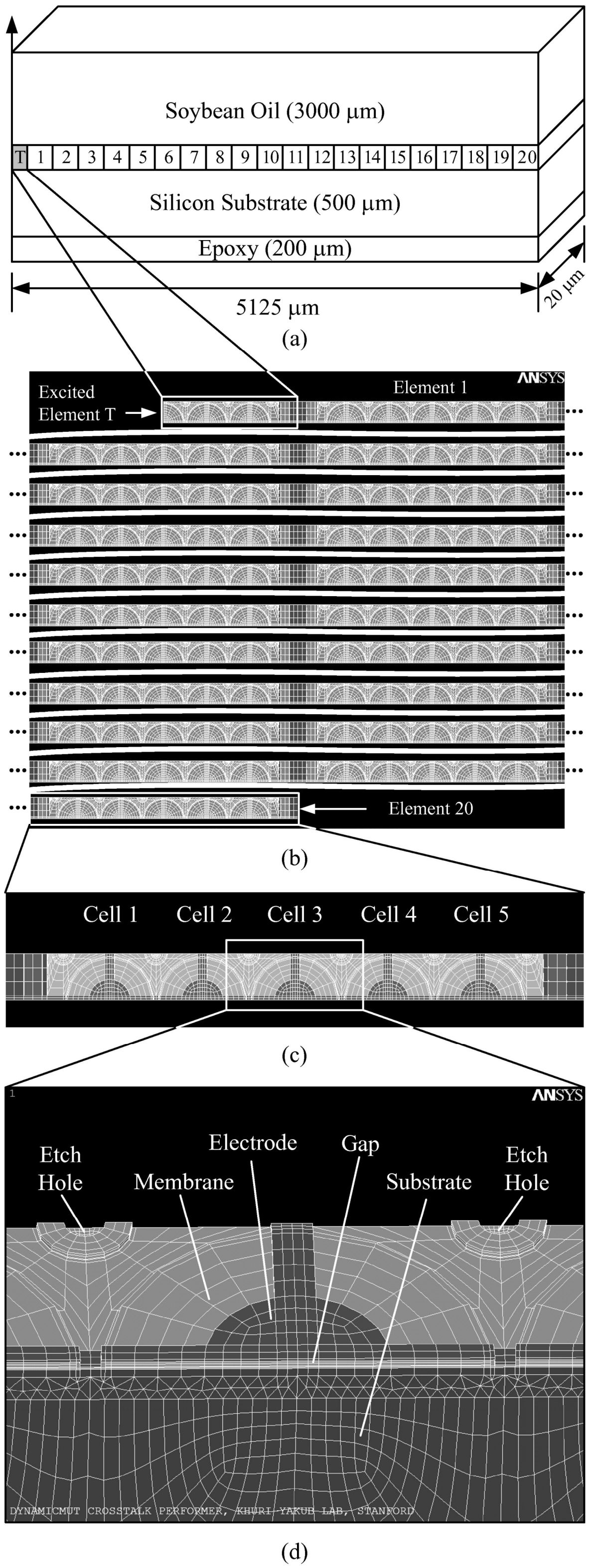

Figure 1. Finite Element Model of the 1-D CMUT array. (a) Schematic description of the complete FEM. (b) Top view of CMUT surface. (c) Magnified view of one CMUT array element surface. (d) Magnified, perspective view of one CMUT cell.

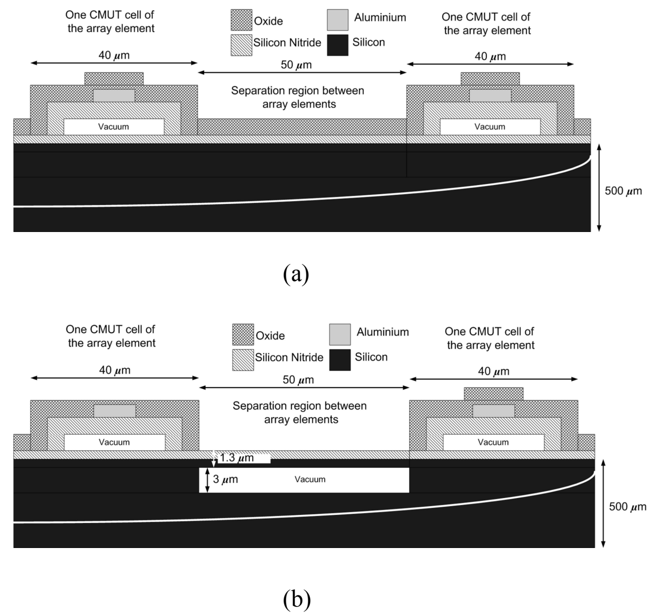

Figure 2. The cross-section of the separation region between the closest cells of the neighboring array elements. The CMUT cells of the array elements are circular. The membrane formed in the separation region is rectangular (50 µm width and infinite length along the 1-D elements). (a) Regular CMUT array: bulk substrate in the separation region. (b) Modified CMUT array: membrane formed in the separation region.

III. RESULTS

The crosstalk displacements from the FEM and the experiment are compared in the frequency-wave number domain for both conventional and collapsed operations in Fig. 3. The details of the measurement setup and the experiments are in [6,8]. Scholte wave, Lamb waves and dispersive guided modes are observed in both the FEM and the experimental crosstalk displacements (Fig. 3). The main crosstalk mechanism is the dispersive guided modes propagating in the fluid-solid interface. Although the transmitter element has a center frequency of 5.8 MHz with more than 130% fractional bandwidth, the guided wave has a center frequency of 2.3 MHz with a narrow bandwidth and has a cut-off frequency of 4 MHz. In the collapsed operation, the cut-off frequency becomes 10 MHz because of the contact between the membrane and the substrate. The FEM results are verified with the experiments in Fig. 3 [8].

The crosstalk results of the regular and the modified CMUT arrays are compared using FEM in Fig. 4. The displacement results in the time-spatial domain show the propagation of the crosstalk waves with little attenuation for the regular CMUT array [Fig. 4(a)] and with higher attenuation for the modified CMUT array [Fig. 4(b)]. The crosstalk level, averaged displacement over the array elements, is improved approximately 10 dB for the modified CMUT array (-34.2) compared to the regular CMUT array (-24.7). The dispersive guided mode for the regular CMUT array has a single peak at 2.3 MHz [Fig. 4(c)], and the crosstalk amplitude decays rapidly away from this frequency. However,

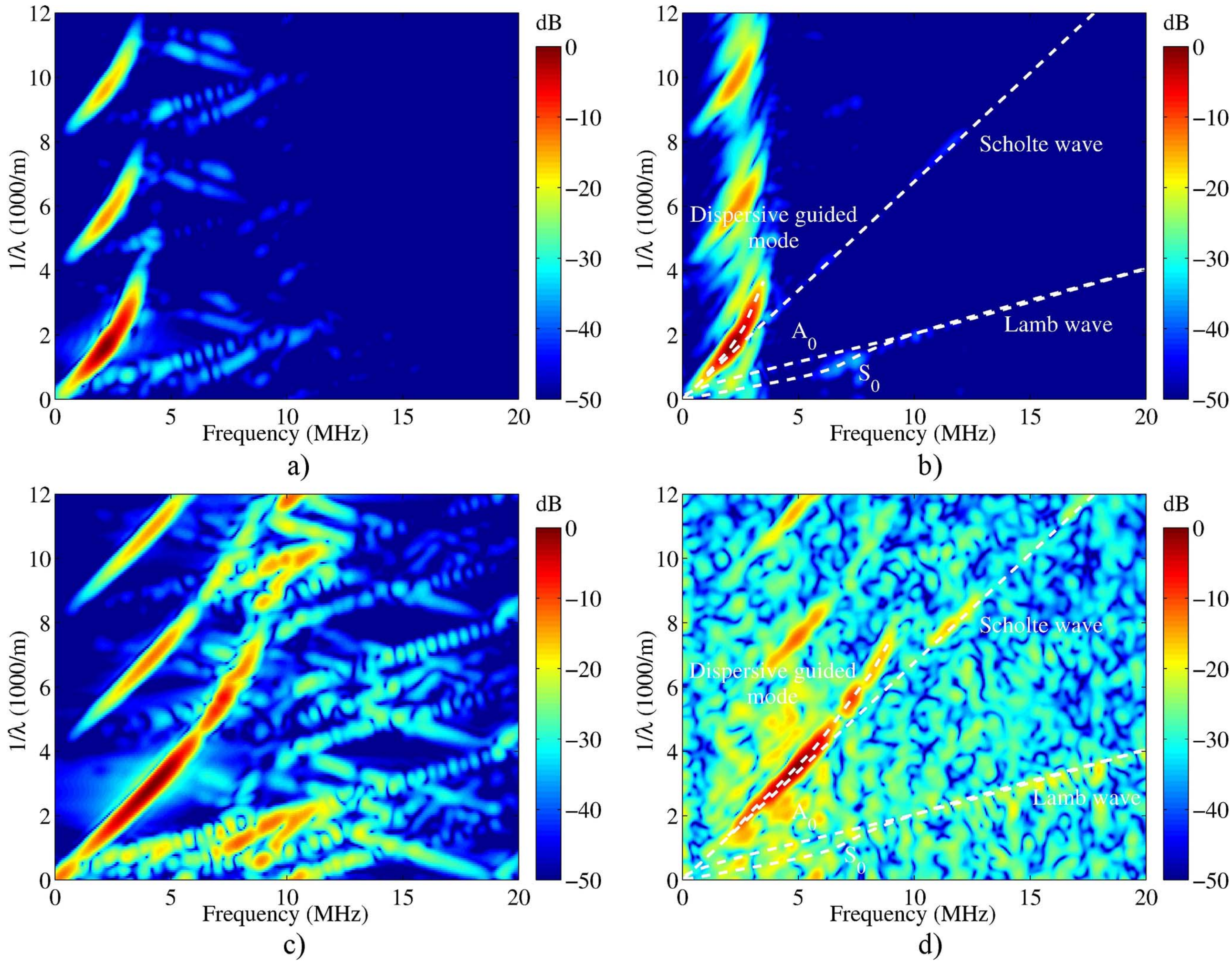

Figure 3. Comparison of the crosstalk displacements of the 1-D CMUT array between the FEM and the experiment in the frequency-wave number domain. (a) FEM results in the conventional operation. (b) Experimental results in the conventional operation. (a) FEM results in the collapsed operation. (a) Experimental results in the collapsed operation.

this mode for the modified CMUT array has two peaks separated by a dip occurring at 1.4 MHz [Fig. 4(d)]. The modification to include the membrane in the separation region between the elements introduces this dip and reduces the crosstalk without loss of acoustic output pressure of the transmitter element.

IV. DISCUSSION

To compare the FEM and the experimental results side by side, we chose to use the displacement results for frequency-wave number domain representations in Fig. 3. The presence of the almost stationary substrate surface between the array elements results in the generation of the multiples of the guided mode in the spectra.

The Lamb wave modes (A_0 and S_0) have higher signal strength in the FEM than the experimental results as a result of the acousto-optic correction implemented for the experimental results [8].

Although the CMUTs are broadband devices in transmit and receive operations, the crosstalk between the array elements is narrowband, and has typically a lower preferred crosstalk frequency than the center frequency. The membranes introduced in the separation region are designed with a cut-off frequency close to this crosstalk frequency. Therefore, the propagation of the crosstalk is no longer supported and suffers from high attenuation. The narrowband of the crosstalk and the cut-off frequency of the separation region membrane make this method not only easy to implement in actual CMUT arrays but also rewarding in better crosstalk performance.

V. CONCLUSION

Crosstalk in 1-D CMUT arrays operating in conventional and collapsed modes was modeled using LS-DYNA. The FEM results are verified with the interferometer measurements. The main crosstalk mechanism is the dispersive guided mode propagating in the fluid-solid interface. A powerful method based on the

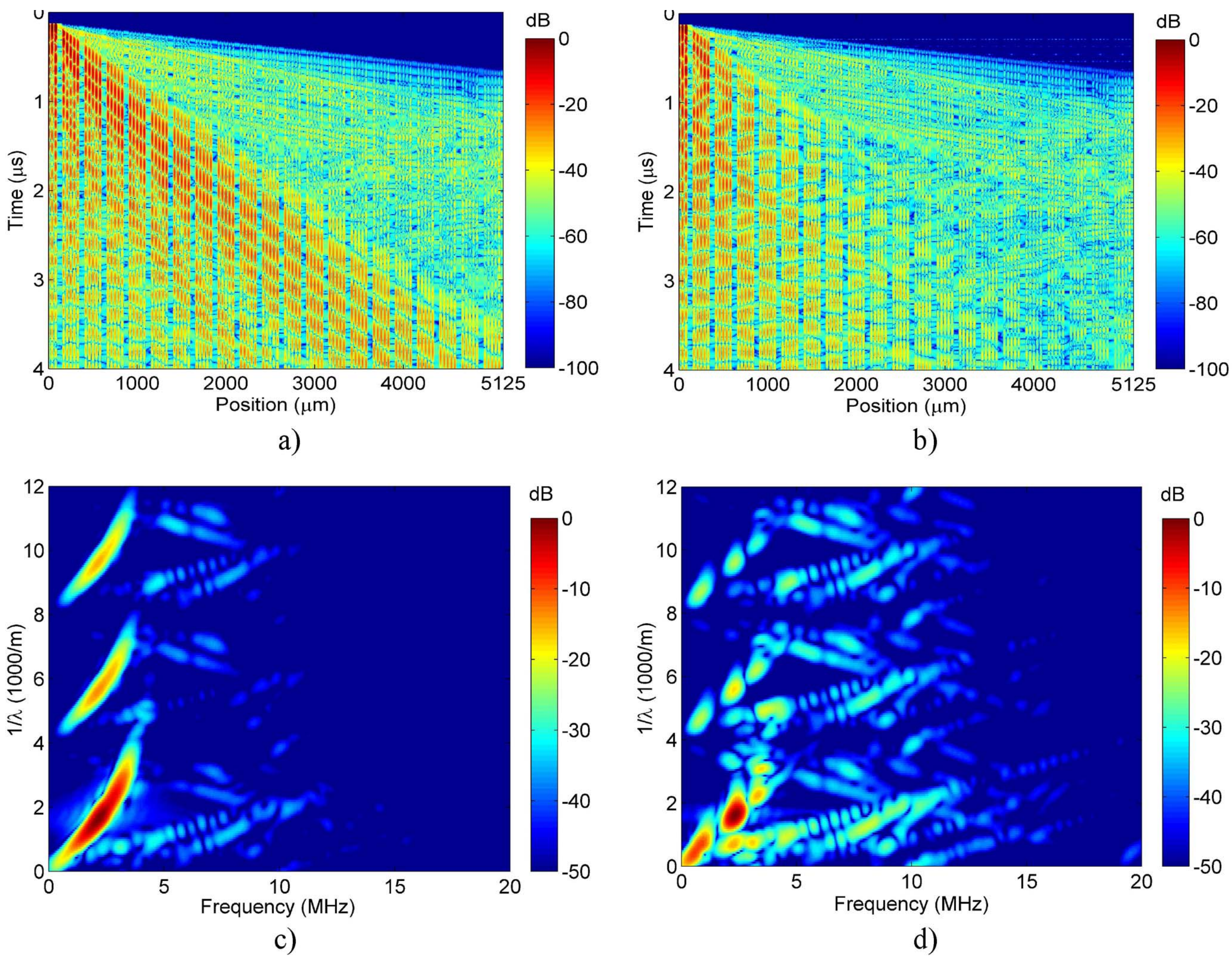

Figure 4. Crosstalk displacements of the regular and the modified CMUT arrays. (a) Time-spatial domain results for regular CMUT array. (b) Time-spatial domain results for modified CMUT array. (c) Frequency-wave number domain results for regular CMUT array. (d) Frequency-wave number domain results for modified CMUT array.

acoustic band gap is presented to reduce the crosstalk without loss of the pressure of the transmitter element.

Acknowledgment

This work is supported by ONR-NIH. Mario Kupnik acknowledges the FWF Austrian Science Fund for financial support.

Reference

[1] D. Certon, N. Felix, E. Lacaze, F. Teston and F. Patat, "Investigation of Cross-coupling in 1-3 Piezocomposite Arrays", *IEEE Trans. on UFFC*, Vol. 48, pp. 85-93, Jan. 2001.

[2] X. Jin, Ö. Oralkan, F.L. Degertekin, and B.T. Khuri-Yakub, "Characterization of One-Dimensional Capacitive Micromachined Ultrasonic Transducer Arrays", *IEEE Trans. on UFFC*, Vol. 48, pp. 750-760, May 2001.

[3] B. Bayram, E. Haeggstrom, G.G. Yaralioglu, and B.T. Khuri-Yakub, "A New Regime for operating Capacitive Micromachined Ultrasonic Transducers", *IEEE Trans. on UFFC*, Vol. 50, pp. 1184-1190, Sep. 2003.

[4] B. Bayram, O. Oralkan, A.S. Ergun, E. Haeggstrom, G.G. Yaralioglu, and B.T. Khuri-Yakub, "Capacitive Micromachined Ultrasonic Transducer Design for High Power Transmission", *IEEE Trans. on UFFC*, Vol. 52, no. 2, pp. 326-339, Feb. 2005.

[5] B. Bayram, G.G. Yaralioglu, M. Kupnik, A.S. Ergun, O. Oralkan,,A. Nikoozadeh, and B.T. Khuri-Yakub, "Dynamic Analysis of Capacitive Micromachined Ultrasonic Transducers", *IEEE Trans. on UFFC*, Vol. 52, no. 12, pp. 2270-2275, Dec. 2005.

[6] B. Bayram, M. Kupnik, G.G. Yaralioglu, O. Oralkan, D. Lin, X. Zhuang, A.S. Ergun, A.F. Sarioglu, S.H. Wong, and B.T. Khuri-Yakub, "Characterization of Cross-Coupling in Capacitive Micromachined Ultrasonic Transducers," in Proc. IEEE Ultrason. Symp., 2005.

[7] LS-DYNA 970 Keyword User's Manual, Livermore Software Technology Corporation, Livermore, CA, 2003.

[8] B. Bayram, M. Kupnik, G.G. Yaralioglu, O. Oralkan, A.S. Ergun, D. Lin, S.H Wong, and B.T. Khuri-Yakub, "Finite Element Modeling and Experimental Characterization of Crosstalk in 1-D CMUT Arrays," accepted for publication in IEEE Trans. Ultrason. Ferroelect., Freq. Contr.