CHARACTERIZATION OF CROSS-COUPLING IN CAPACITIVE MICROMACHINED ULTRASONIC TRANSDUCERS

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Abstract – **This paper analyzes element-to-element and cell-to-cell cross-coupling in capacitive micromachined ultrasonic transducers (cMUTs) using an interferometer. In a 1-D linear cMUT array immersed in oil, a single element was excited, and membrane displacements were measured at different positions along the array with an interferometer. Electrical measurements of the received voltage on each array element were also performed simultaneously to verify the optical measurements. The array was then covered with a polydimethylsiloxane (PDMS) layer, and the cross-coupling measurements were repeated. The cross-coupling levels for conventional and collapsed operation of the cMUT were compared. Since the cMUTs were immersed in oil, the optical measurements were corrected for acousto-optic interaction, and the results were reviewed in time-spatial and frequency-spatial domains. The main cross-coupling mechanism was due to the dispersive guided modes supported by the membrane periodicity. In both modes of operation, cross-coupling dispersion curves predicted a gradual reduction in phase velocity at higher frequencies. At lower frequencies, this phase velocity tended to approach 1480 m/s asymptotically. Better cross-coupling suppression was observed in the collapsed (-34 dB) than the conventional operation (-23 dB). The element-to-element cross-coupling experiments showed that a 5-µm PDMS layer reduced the measured cross-coupling levels down to -39 dB in the collapsed operation.**

I. INTRODUCTION

Cross-coupling is a major issue for the ultrasound transducers, and was previously addressed for piezoelectric transducers [1-2] and capacitive micromachined ultrasonic transducers [3]. The purpose of this paper is to experimentally determine the cross-coupling mechanisms for a 1-D cMUT array. Optical displacement measurements using an interferometer were compared with electrical measurements of the received voltages in neighboring elements. Good agreement between optical and electrical results was observed.

Electrical measurements limited the spatial resolution to the pitch of the array (element-to-element spacing), whereas higher spatial resolution was possible with optical measurements (cell-to-cell spacing). Electromagnetic interference and inadequate separation of the excited and the close neighbor elements in time domain were some other disadvantages of the electrical measurements. Optical displacement measurements on the membrane surface along the elements were immune to the disadvantages of the electrical method. The optical measurements were corrected to eliminate the acousto-optic interaction due to the refractive index of the oil and the pressure created in the oil [4]. The optical time domain measurements were analyzed in the wave number-frequency (*k*-*w*) domain for the multi-mode wave propagation [5].

Conventional and collapsed operations of the cMUT were compared, and the influence of a 5-µm polydimethylsiloxane (PDMS) layer covering the cMUT was investigated. The main cross-coupling mechanism was due to the dispersive guided modes. Interface waves (Stoneley-Scholte) and surface waves (Rayleigh) were relatively weak in cross-coupling [3]. The dispersive guided modes were determined for conventional and collapsed operations and corresponding *k*-*w* diagrams were analyzed.

II. EXPERIMENT

The experimental setup (Fig. 1) enabled both electrical and optical measurements to be performed simultaneously. A DC bias supply (PS300, Stanford Research Systems, Sunnyvale, CA, USA) was used to bias all the elements of the array, and a function generator (HP8112A, Agilent Technologies Inc., Palo Alto, CA, USA) was used to excite the transmit element with one-cycle sinusoidal or unipolar pulse. Electrical signals were measured on a digital oscilloscope (Infiniium 500 MHz, 2GS/s, Agilent Technologies Inc., Palo Alto, CA, USA) by probing individual array elements. The optical measurements were made using an optical fiber interferometer OFV-511 (Polytec GmbH, Waldbronn, Germany) connected to an vibrometer controller OFV-2700/2 (Polytec) that contained a modified wideband displacement decoder OVD-30 (Polytec) with an extended frequency range (50 kHz-30 MHz). A common personal computer (PC) was used to process the data transferred over a GPIB-IEEE 488 bus from the oscilloscope. LabView™ Version 6.0 software (National Instruments, Austin, TX, USA) was used to control the x-y stage and gather the electrical and optical data.

The cMUT was immersed in vegetable oil, and the distance from the CMUT to the air-oil interface was adjusted to 9 mm to avoid the reflected ultrasonic waves. Using the microscope and the x-y stage, the cMUT surface was aligned with the laser light.

The 1-D 64-element cMUT array (f_{CENTER}=4.5 MHz in oil, $V_{COLLAPSE}$=30 V) used in this paper is shown in Fig. 2. The center element was excited, and the optical measurements were performed over the metal line passing across the center of the 5-cells of each element, keeping the laser beam focused on the

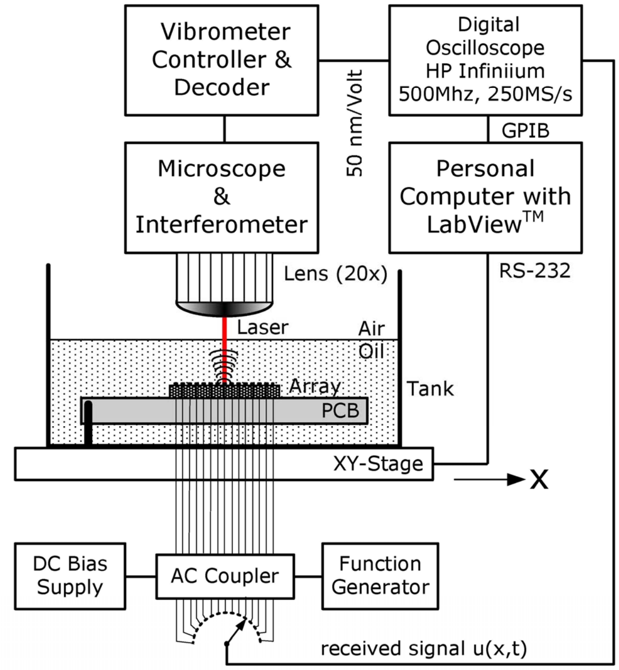

Figure 1. Experimental Setup

surface. To eliminate the effect of acousto-optic interaction, the laser beam was initially focused on the posts of the cells, where the actual displacement would be negligible in comparison to that of the cells. Assuming the posts to be fixed, the interferometer data gathered on the posts was later used to correct for the actual membrane displacements. These membrane displacements on the metal line scan were averaged over each cell. The cell-to-cell separation within each element is 40 µm whereas the cell-to-cell separation of each neighboring element is 90 µm. Piecewise linear approximation was used to convert into uniformly sampled data at 10 µm.

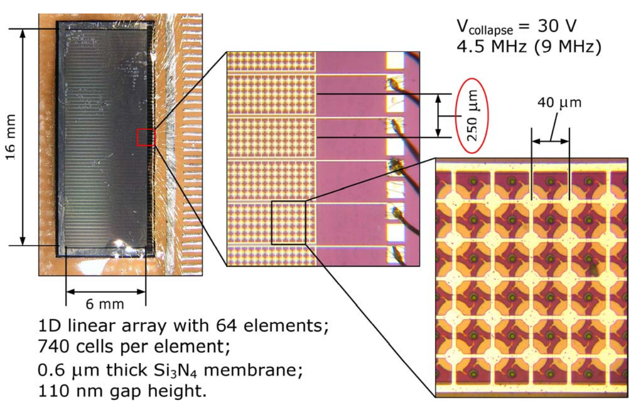

Figure 2. 1-D CMUT Array used in cross-coupling experiments

III. Results

The electrical and optical measurements (the received voltage and the displacement, respectively) are compared for the 9th neighboring element of the transmitting element in Fig. 3. A 20-ns, +10-V unipolar pulse was applied at a bias voltage of 25 V.

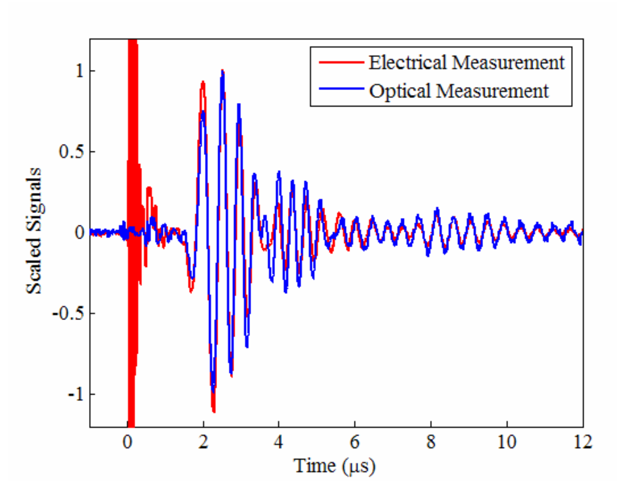

Figure 3. Electrical and optical measurements

Figure 4 shows the electrical measurement in the time-spatial domain. A 4.5 MHz, 10-V_{PP} one-cycle sinusoidal pulse was applied at a bias voltage of 25 V.

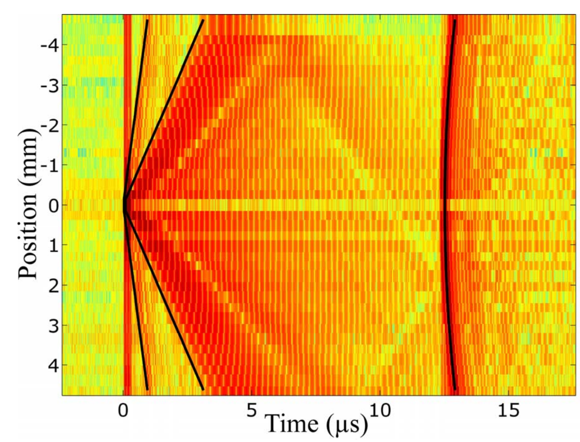

Figure 4. Electrical measurement in time-spatial domain. The excited element is positioned in the origin. The black lines, representing 4900 m/s (Rayleigh surface wave) and 1480 m/s (Stoneley-Scholte interface wave) are also drawn. The curved line between 10 µs and 15 µs corresponds to the calculated arrival of the reflected ultrasonic wave from the air-oil interface.

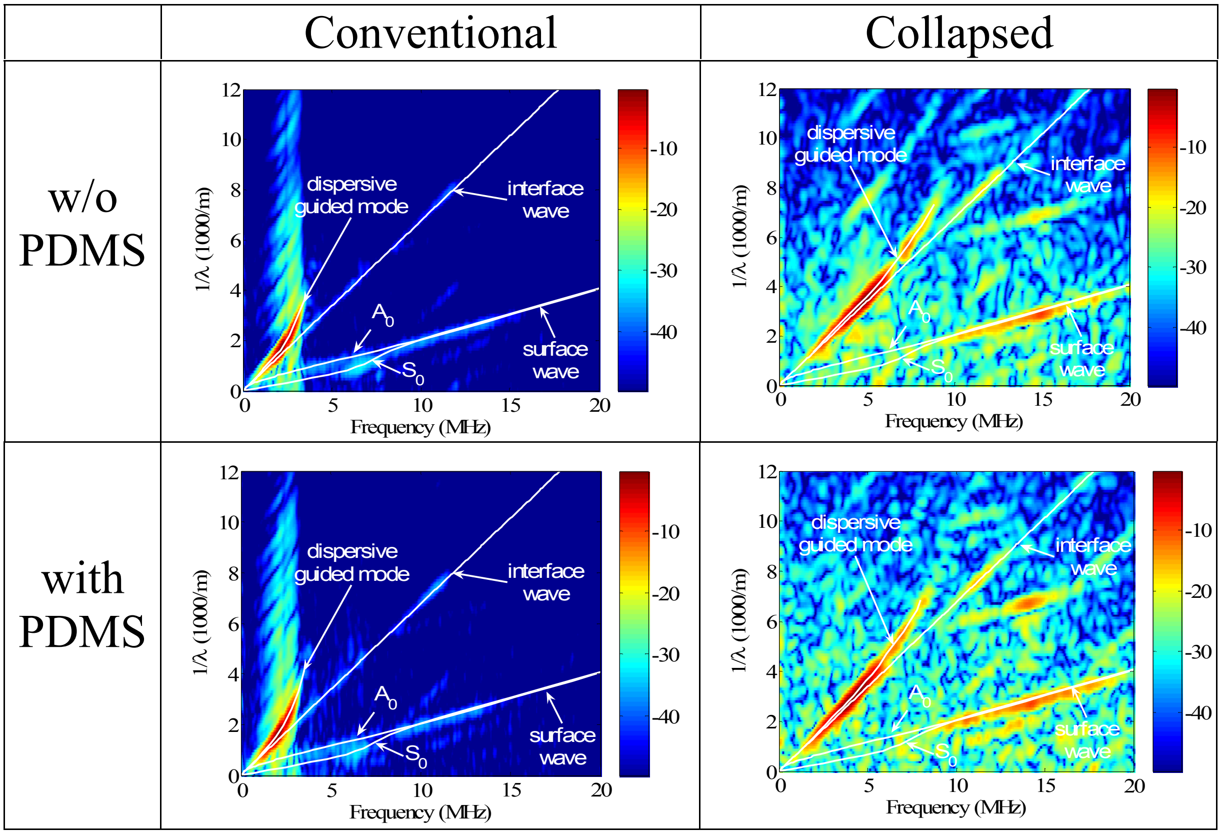

Figure 5. Cross-coupling waves in frequency-spatial (*w-k*) domain. Operational modes (Conventional vs. Collapsed) and influence of 5-µm PDMS coverage on the cMUT surface are compared. Interface waves (Stoneley-Scholte, 1480 m/s), surface waves (Rayleigh, A_0, S_0 modes) and dispersive guided waves are shown. Dispersive guided waves are the most dominant cross-coupling component in all considered cases.

The optical measurement data is presented in the wave number-frequency domain in Fig. 5. Conventional (25 V bias) and collapsed (40 V bias) operations were investigated for cMUTs with a 20-ns, +10-V unipolar pulse. The center frequency of the transmitting element (w/o PDMS) was 4.5 MHz and 9 MHz in conventional and collapsed operations, respectively. However, the dispersive guided waves had a center frequency of 2.1 MHz in conventional, and 4.5 MHz in collapsed operations. Addition of 5-µm PDMS on the cMUT surface only changed these results slightly. Dispersive guided waves were the most dominant cross-coupling component in all considered cases. The presence of interface and surface waves were also observed and found to be in agreement with theory [6]. Surface and interface waves appeared to be stronger in the collapsed operation than the conventional operation when compared with the dominant dispersive waves.

The phase velocities of the dispersive guided waves are depicted in Fig. 6. In conventional operation, the phase velocity monotonically reduces from 1500 m/s at 0.5 MHz to 950 m/s at 3.5 MHz. In collapsed operation, the phase velocity reduces from 1450 m/s at 2 MHz to 1200 m/s at 9 MHz. Coverage of PDMS on the cMUT slightly reduces the phase velocity for both operation modes.

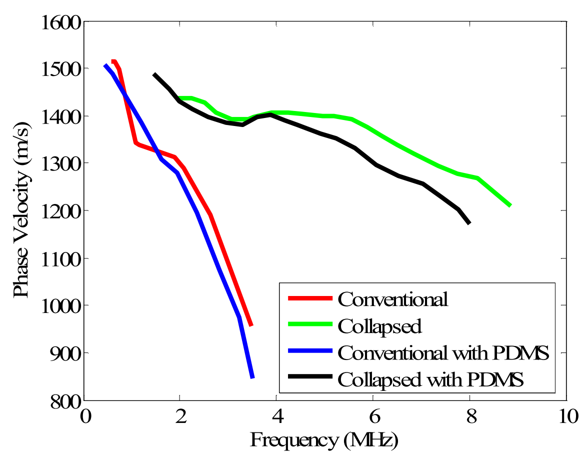

Figure 6. Phase velocity of the dispersive guided waves

The cross-coupling peak-to-peak amplitudes were normalized to the peak-to-peak transmit amplitudes (Fig. 7). Cross-coupling in conventional operation was -23 dB, and addition of PDMS covering hardly made any improvement. Collapsed operation reduced cross-coupling to -34 dB, which corresponded to 11 dB more suppression than the conventional operation. Coverage of PDMS in collapsed operation reduced cross-coupling to -39 dB.

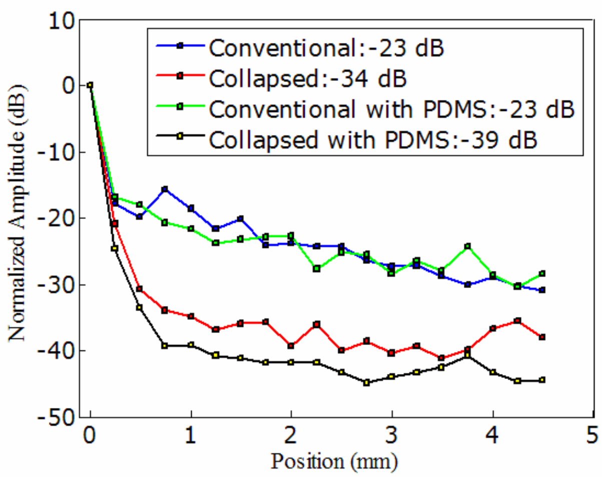

Figure 7. Cross-coupling normalized amplitude. A 20-ns, +10 V unipolar pulse was applied.

IV. Discussion

Optical measurements using an interferometer allowed precise measurements and improved understanding of cross-coupling waves in cMUTs. Electrical measurements represented the cumulative behavior of one element (740 cells, 5 cells in width), whereas optical measurements enabled the behavior of each cell to be investigated independently. Because immersion in oil caused acousto-optic interaction, line integration of the pressure in the oil along the laser beam as a function of time was necessary for correction [4]. Finite element method (FEM) calculations, described in [7], were used to determine that the line integral of the pressure on the center and on the post of the cMUT differed less than 10% for an infinitely large cMUT. Therefore, the acousto-optic interaction on the cMUT membrane was assumed to be equal to that on the posts. Optical and electrical measurements were compared side by side for verification (Fig. 3). Electrical measurements, depicted in Fig. 4, are also in good agreement with the corresponding optical measurements.

Surface waves, interface waves, and the dispersive guided modes were observed in the cross-coupling of cMUTs (Fig. 5). However, dispersive guided waves are the most dominant cross-coupling factor (Fig. 5). The presence of these waves was calculated by finite element analysis in [8-9]. The phase difference between the cells of the cMUT resulted in these dispersive guided modes [8]. In our analysis, the cells were separated in position, and they received the cross-coupling waves at different times, resulting in the phase difference.

Collapsed operation increased the center frequency of cross-coupling wave from 2.1 MHz to 4.5 MHz. Surface waves also became stronger in collapse mode due to the contact between the membrane center and the substrate (Fig. 5). The phase velocity varied less as a function of frequency in collapsed operation (1450-1200 m/s over 2-8 MHz range) than the conventional operation (1500-950 m/s 0.5-3.5 MHz range) in Fig. 6. Better understanding of the dispersive guided modes requires a finite element analysis of a similarly constructed model of the experimental setup.

Collapsed operation improved cross-coupling suppression (Fig. 7). Coverage with 5-µm PDMS was relatively ineffective in conventional operation, but improved the cross-coupling by 5 dB in collapsed operation. This improvement might be due to the higher center frequency of collapsed operation, resulting in more loss in PDMS. Influence of thicker PDMS coverage is currently under investigation.

V. Conclusion

Dispersive guided modes are the main source of cross-coupling in cMUT arrays. Interface (Stoneley-Scholte) and surface (Rayleigh) waves do not play a significant role, though they are still present in cross-coupling. Collapsed operation reduces the cross-coupling to -34 dB, which is a significant reduction compared to -23 dB in conventional operation. PDMS covering also appears to reduce cross-coupling more in collapsed operation.

Acknowledgment

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