Capacitive micromachined ultrasonic transducer arrays as tunable acoustic metamaterials

Shane W. Lani,^{1,a)} M. Wasequr Rashid,² Jennifer Hasler,² Karim G. Sabra,¹ and F. Levent Degertekin^{1,2}

¹*George W. Woodruff School of Mechanical Engineering, Georgia Institute of Technology, 801 Ferst Drive, Georgia 30332-0405, USA*

²*School of Electrical and Computer Engineering, Georgia Institute of Technology, Van Leer Electrical Engineering Building, 777 Atlantic Drive NW, Atlanta, Georgia 30332-0250, USA*

(Received 31 October 2013; accepted 26 January 2014; published online 7 February 2014)

Capacitive Micromachined Ultrasonic Transducers (CMUTs) operating in immersion support dispersive evanescent waves due to the subwavelength periodic structure of electrostatically actuated membranes in the array. Evanescent wave characteristics also depend on the membrane resonance which is modified by the externally applied bias voltage, offering a mechanism to tune the CMUT array as an acoustic metamaterial. The dispersion and tunability characteristics are examined using a computationally efficient, mutual radiation impedance based approach to model a finite-size array and realistic parameters of variation. The simulations are verified, and tunability is demonstrated by experiments on a linear CMUT array operating in 2-12 MHz range. © 2014 AIP Publishing LLC. [<http://dx.doi.org/10.1063/1.4864635>]

Capacitive micromachined ultrasonic transducer (CMUT) arrays are promising devices for ultrasonic imaging due to their easy and flexible fabrication in addition to their relatively wide bandwidth compared to the typically used piezoelectric transducers.¹ The CMUT arrays are composed of many micromachined thin membranes that can be actuated and detected capacitively. When used in immersion, the mechanical coupling between the CMUT membranes results in acoustic cross-talk within the array elements.²⁻⁴ The main component of acoustic crosstalk has been identified as an evanescent wave above the CMUT array supported by the periodic membranes and the resonance of the individual membranes, which are similar to Rayleigh-Bloch waves in terms of field distribution.^{2,4,5} For typical imaging applications, these waves degrade the performance of the array in the frequency regime of the crosstalk by a poor angular response and range resolution, and hence much research has been done to reduce the effects of these waves.^{6,7} In contrast, this work characterizes the wave propagation across the surface of CMUT arrays for the potential use for externally tunable acoustic filters or subwavelength focusing by studying the CMUT array as a metamaterial.

Most CMUT arrays consist of subwavelength-sized membranes arranged in a periodic pattern on a silicon substrate. The surface acoustic waves across CMUT arrays derive their properties not only from the periodic spacing of the array but also upon the resonance of each membrane.⁸ Since the resonance of the CMUT membrane can be easily tuned by changing the DC bias voltage,⁹ the CMUT arrays are in effect a tunable metamaterial in a way unlike other current tunable metamaterials.¹⁰⁻¹² Other tunable metamaterials focus on changing either the periodicity or the elastic characteristics of the material by relying on external stimuli such as an external stress to change the dimensions of the

metamaterial. While an electric field has been used before to tune metamaterials, it has been done so to alter the geometry of a dielectric elastomer and not to alter a resonance as demonstrated here.^{12,13} This Letter investigates the dispersive surface wave present on CMUT arrays in immersion using a linear semi-analytic model, which solves for transient behavior of finite size CMUT arrays. The model is based on calculating the mutual impedance between each membrane, and it accurately predicts how energy is propagating in a given frequency band. This approach is different from calculating the Bloch mode expansion about a unit cell which calculates the entire band structure for an infinite approximation with a perfect medium.¹² The model is verified through experiments on a 1-D CMUT array designed to operate in the 2-12 MHz range when immersed in water. The tunability of the CMUT array is also demonstrated on the same array by using different bias voltages with the results compared to the calculations.

There are two main methods to study a periodic structure; (1) solving the infinite case with the Bloch theorem over a unit cell or (2) solving the finite array case by calculating the mutual impedances of each unit cell to each other.¹⁴ The Bloch theorem is used to find the entire band structure of the metamaterial which is useful in some aspects, but it has limitations for realistic modeling of how energy is propagating across a finite structure. To match transient experimental results on a finite sized CMUT array, the method of solving the mutual impedances is a more suitable option and will be used for this Letter. Since the mutual impedance model solves a system over a finite array it also has the ability to individually parameterize each CMUT membrane as opposed to the Bloch theorem which is restricted by symmetry and the unit or super cell. This means that each membrane can be individually positioned (in periodic or aperiodic fashion) and individually parameterized such as varying each membrane thickness or applied voltage. The membrane variations are easy to implement and end up

^{a)}Authors to whom correspondence should be addressed. Electronic addresses: shane.w.lani@gmail.com; karim.sabra@me.gatech.edu; and levent.degertekin@me.gatech.edu

disrupting the resonance of the Bloch modes of the array. This makes the model more realistic allowing the simulations to match the experiments more closely.⁸ This model was originally introduced by Meynier *et al.* and will be briefly reviewed.¹⁵ The CMUT array surface is modeled as a two dimensional nodal mesh, and for each frequency of interest, a force balance equation is solved for the displacement, $\{\tilde{u}\}$, for each node

$$\{n\}\tilde{V} = [[K] - [K_{ss}] - \omega^2[M] + j\omega[Z_{mur}]]\{\tilde{u}\}. \quad (1)$$

The force balance encompasses four effects from (1) the linearized electrostatic actuation with associated parameters of voltage applied, $\tilde{V}$, to the active membranes, n , and the spring softening effect, K_{ss} , (2) the stiffness derived from a finite difference method, K , (3) the mass, M , and (4) pressure forces from the fluid in the form of mutual radiation impedance, Z_{mur} . The mutual radiation impedance is computed by a boundary element method (BEM) which is derived from the Green's function of a baffled point source in a semi-infinite fluid. This mutual radiation impedance term contains the coupling between each membrane and accounts for the evanescent wave above the CMUT array.

The model is used to obtain information on the traveling surface waves. In order to estimate the group velocity of these surface waves a time-frequency transform, the Smoothed Pseudo Wigner-Ville (SPWV) transformation, is applied to the simulated and measured waveforms. This transform computes the time-frequency representation of a signal, $s(t)$, and uses time and frequency smoothing windows, functions h and g , to reduce the interference patterns inherent to the Wigner-Ville transform¹⁶

$$SPWV(t, \omega) = \int_{-\infty}^{+\infty} h(\tau) \frac{1}{2\pi} \int_{-\infty}^{+\infty} g(u - t) s\left(u + \frac{\tau}{2}\right) s^* \times \left(u - \frac{\tau}{2}\right) du e^{-j\tau\omega} d\tau. \quad (2)$$

The SPWV provides a means for estimating the arrival time of energy for the traveling waves at different frequencies which yields in turn an estimate of the group speed. The proposed modeling approach, along with the addition of the SPWV, allows for rapid examination of the surface wave's dispersive features with a variety of membrane parameters and finite array dimensions resulting in realistic results to compare with actual experiments.

The CMUT array used in the experiments is shown in Figure 1. Each element ($2.465 \text{ mm} \times 0.245 \text{ mm}$) is composed of 180 membranes arranged in a 45×4 grid with each membrane having the lateral dimensions of $45 \mu\text{m}$ by $45 \mu\text{m}$, a thickness of $2.2 \mu\text{m}$, and a gap of 47 nm . The membranes have a resonance frequency of 12 MHz in air with the collapse voltage of 38 V , and they operate in the frequency range of $2\text{--}12 \text{ MHz}$ in immersion. Note that these arrays were originally designed for ultrasonic imaging applications, not for the particular study presented here. Figure 1(a) is the top view of the CMUT array showing a portion of the elements (delimited by dashed lines) composed of many membranes with the electrodes running through the membranes. The electrodes for

FIG. 1. (a) Top view of CMUT array zoomed in highlighting the size of one membrane and portion of one element delimited by the yellow dashed lines. The lighter rectangles running along the element and through the membranes are the top electrodes. (b) Full 1×16 CMUT array with wire bond pads and connections used in experiments. (c) (dimensions not to scale) Electrical schematic of the connections to the CMUT array showing that all elements are biased by V_{bias} via the bottom electrode and the center elements (Elmt. 2–15) can have a different bias through the V_{biasC} connection.

each element connect the membranes of one element electrically in parallel. The entire experimental array with the first element on the left (transmitter) and the sixteenth element on the right (receiver) is shown in Figure 1(b) along with the wire bonds to the electronics. This array geometry essentially forces 1-D waves generated by the transmitter (Elmt. 1) to propagate on a special medium made of periodic CMUT membranes (Elmt. 2–15) to the receiver (Elmt. 16), making it suitable to study the characteristics of the evanescent surface waves of interest here.

The experiments use the 1×16 array in a deep-water bath with two different DC bias levels applied on the array as depicted in the electrical schematic of Figure 1(c). All elements in the CMUTs array have a common voltage (V_{bias}) applied to the bottom electrode which is fixed on the silicon substrate while the middle elements (Elements 2–15) are biased by a separate power supply at different levels (V_{biasC}). This allows the transmitter and receiver to have a high sensitivity while the bias of the middle elements that are part of the propagation medium can be altered to study the effect of

different DC bias levels on the evanescent surface wave. The transmitter is excited with a 2 V, 40 ns pulse, and the receiver's signal is recorded and sampled at 500 MHz after being amplified by a transimpedance amplifier (TIA). Figure 2 shows the calculated transient normalized average velocity signal over the receiver CMUT (Element 16) (Fig. 2(a)) and the measured TIA output voltage (Fig. 2(c)), which is proportional to the average velocity.¹⁷ The SPWV transform results are shown under the corresponding time signal. In this particular case, the difference between V_{bias} and V_{biasC} is 0 V, and this difference will be hereby referred to as the bias on the middle elements. The simulation modeled each element in the 1×16 array as 5×4 membranes instead of 4×45 membranes of the actual element for computational efficiency. To account for the variation of membrane properties over the array, the simulation also varied the parameters of the membrane by applying a normal distribution to the applied bias voltage with a zero mean and standard deviation of 0.14 V.

The initial arrival time of $2.5 \mu\text{s}$ and the dispersive nature of the signal, higher frequencies arriving later, are well

FIG. 2. The transmitter (Elmt. 1) was excited with a 40 ns pulse (a) normalized velocity of the receiver (Elmt. 16) from simulation. (b) Time-frequency plot using the SPWV of the velocity from receiver from simulation (c) normalized measured voltage of the receiver from experiment. (d) Time-frequency plot using the SPWV of the velocity from receiver from experiment.

predicted by the simulations. The amplitude dip in the signals around $4.5 \mu\text{s}$ in time (Figs. 2(a) and 2(c)) is due to destructive interference resulting from the wavelength of the evanescent wave matching the total width of the CMUT array element of $245 \mu\text{m}$. This arrival corresponds to the arrival time for 5 MHz traveling with phase speed of 1300 m/s (computed by simulation). The later arrivals (after $4.5 \mu\text{s}$) are due to slow waves and are nearly standing waves at around 6–6.5 MHz, where the group speed of the evanescent wave approaches zero.⁸ Beyond this frequency, there is no significant energy flow, indicating a stop band. This also has implications on the CMUT array crosstalk, as these waves exist below the stop band edge which is mainly determined by the first resonance frequency of the single isolated membrane in immersion. Therefore, one may want to operate the CMUT array above this frequency for far field imaging using bulk waves in the immersion medium to avoid crosstalk.

To demonstrate that this stop band can be tuned electrically by altering the membrane resonance, the center elements are biased with two other voltage levels of 30 V and 35 V. The Fourier transform of the first $8 \mu\text{s}$ of each signal received is evaluated to determine at which frequencies the evanescent wave is carrying energy effectively along the array from the transmitter to the receiver. These transmission spectra are plotted in Figure 3 for both the simulations and the experiments for 0 V (Fig. 3(a)), 30 V (Fig. 3(b)), and

FIG. 3. Transmission spectra of the first $8 \mu\text{s}$ for both the simulation (blue solid line) and experiment (red dashed line) for (a) center bias at 0% of collapse (b) center bias at 75% of collapse and (c) center bias at 95% of collapse which show a stop band that shifts to lower frequency as the bias level is increased from 0% of collapse (band stop of 6.5 MHz) to 75% and 95% of collapse which have a band stop of 5 MHz and 3.5 MHz, respectively.

35 V bias case (Fig. 3(c)). The frequency spectrum of the 0V bias case for both the simulation (blue solid line) and experiment (red dashed line) agree well with each other as both show energy in a frequency band from 2–5 MHz and a narrowband around 6 MHz along with a stop band edge at 6.5 MHz. The dip in the frequency response around 5 MHz is due to destructive interference as explained earlier, and the small dips in the 2–4 MHz band are due to edge effects in the simulations. Above the stop band the experimental transmission spectra contains some energy, albeit 20 dB below the pass band. In this region there is some bulk wave transmission in the fluid medium as predicted, but the main component is the elastic waves excited in the silicon substrate that reradiate energy to the CMUT elements, which the simulation does not account for. As the bias level for the center elements is increased to 30 V and 35 V, the stop band first shifts to 5 MHz (Fig. 3(b)) and then to 3.5 MHz (Fig. 3(c)). This is because the dispersive nature of the surface waves are determined from not only the periodic structure but also the effective mass and stiffness of the CMUT membranes.^{4,18} As the bias voltage is increased, the stiffness of the membranes is reduced due to the spring softening effect while the mass remains fixed and in turn lowers the membrane resonance causing the shifting band stop.⁹ The simulations of transmitted signal spectra at different bias voltages are in agreement with measurements and predict the shift in the stop band edge especially well. Overall, these results indicate that the particular CMUT array has the characteristics of a metamaterial based acoustic filter with an electrically tunable range from 6.5 MHz to 3.5 MHz with a drop off of about 25 dB.

The periodic structure of the CMUT array membranes and the supported evanescent surface waves have characteristics similar to that of coupled resonators used for subwavelength focusing, as demonstrated by Lemoult *et al.*¹⁸ In addition, as an actively controlled array of resonators, the subsonic group speed of the surface waves over the CMUT array can be adjusted by applied bias. The group speeds were obtained from the SPWV analysis of the simulations and experimental signals with a least squares fit to an exponential function with the results shown in Figure 4 for different bias voltages. Both the simulation (solid lines) and the experiments (dashed lines) are in agreement while showing that the group speed approaches zero near the stop band. This feature, and the fact that every membrane in the CMUT array can potentially be used as a transmitter and receiver, offers great promise for subwavelength focusing and imaging based on Bloch modes with controllable resolution in the tens of MHz range while immersed in a fluid.

In summary, finite size periodic CMUT membrane arrays operating in immersion are shown to possess the characteristics of an electrically controllable acoustic metamaterial. This is predicted by combining a BEM based acoustic model and SPWV analysis to obtain the transient response, group speed dispersion, and transmission spectrum between a transmitter and receiver located on a 1-D CMUT array at different bias voltage levels. The predictions are verified by experiments which indicate an electrically tunable transmission spectrum with a clear stop band and tunable subsonic dispersion characteristics in immersion. This phenomenon

FIG. 4. The group speeds as obtained by the simulations (solid lines) and the experimental results (dashed lines) for different DC bias voltages applied to the center elements. The group speeds were calculated using the separation distance between the elements and the energy arrival time obtained by the SPWV.

has implications for CMUT array design to reduce crosstalk. Future work will exploit the CMUT structures as tunable and active acoustic periodic media in immersion for near surface subwavelength imaging and focusing with potential applications in the biological domain.

This work was supported by NSF grant (No. ECCS-1202118) and NIH grant (No. EB010070).

- ¹F. Degertekin, R. Guldiken, and M. Karaman, *IEEE Trans. Ultrason. Ferroelectr. Freq. Control* **53**(2), 474–482 (2006).
- ²X. Jin, O. Oralkan, F. L. Degertekin, and B. T. Khuri-Yakub, *IEEE Trans. Ultrason. Ferroelectr. Freq. Control* **48**(3), 750–760 (2001).
- ³B. Bayram, M. Kupnik, G. G. Yaralioglu, O. Oralkan, A. S. Ergun, D. Lin, S. H. Wong, and B. T. Khuri-Yakub, *IEEE Trans. Ultrason. Ferroelectr. Freq. Control* **54**(2), 418–430 (2007).
- ⁴P.-C. Eccardt, A. Lohfink, and H.-G. Garssen, in *Proceedings of the IEEE International Ultrasonics Symposium, Rotterdam, Netherlands* (2005), pp. 593–596.
- ⁵R. Porter and D. V. Evans, *J. Fluid Mech.* **386**, 233–258 (1999).
- ⁶J. F. Dias, *Ultrason. Imag.* **4**, 1137–1139 (1982).
- ⁷S. Zhou and J. A. Hossack, *IEEE Trans. Ultrason. Ferroelectr. Freq. Control* **54**(6), 1217–1228 (2007).
- ⁸S. Lani, M. W. Rashid, K. G. Sabra, and F. L. Degertekin, in *Proceedings of the IEEE International Ultrasonics Symposium, Prague Czech Republic* (2013), pp. 717–720.
- ⁹H. Torun, K. K. Sarangapani, and F. L. Degertekin, *Appl. Phys. Lett.* **91**, 253113 (2007).
- ¹⁰K. Bertoldi and M. C. Boyce, *Phys. Rev. B* **77**, 052105 (2008).
- ¹¹Z. Liang, M. Willatzen, J. Li, and J. Christensen, *Sci. Rep.* **2**, 859 (2012).
- ¹²P. A. Deymier, *Acoustic Metamaterials and Phononic Crystals* (Springer, 2013).
- ¹³W. P. Yang, L. Y. Wu, and L. W. Chen, *J. Phys. D* **41**, 135408 (2008).
- ¹⁴B. A. Munk, *Frequency Selective Surfaces* (John Wiley & Sons, Inc., 2000).
- ¹⁵C. Meynier, F. Teston, and D. Certon, *J. Acoust. Soc. Am.* **128**, 2549–2561 (2010).
- ¹⁶L. Cohen, *Time Frequency Analysis: Theory and Applications* (Prentice Hall PTR, 1995).
- ¹⁷G. Gurun, P. Hasler, and F. L. Degertekin, *IEEE Trans. Ultrason. Ferroelectr. Freq. Control* **58**(8), 1658–1668 (2011).
- ¹⁸F. Lemoult, M. Fink, and G. Lerosey, *Phys. Rev. Lett.* **107**, 064301 (2011).