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**Bayram et al.**

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# (54) ACOUSTIC CROSSTALK REDUCTION FOR CAPACITIVE MICROMACHINED ULTRASONIC TRANSDUCERS IN IMMERSION

(75) Inventors: **Baris Bayram**, Stanford, CA (US); **Butrus T. Khuri-Yakub**, Palo Alto, CA (US)

(73) Assignee: **The Board of Trustees of the Leland Stanford Junior University**, Palo Alto, CA (US)

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(51) **Int. Cl.**
*H01L 41/08* (2006.01)

(52) **U.S. Cl.** .................................................... **310/328**

(58) **Field of Classification Search** ................. 310/309, 310/311, 324, 320, 327; 367/181, 163; 600/459, 600/437; *H04R 19/00, 1/00*

See application file for complete search history.

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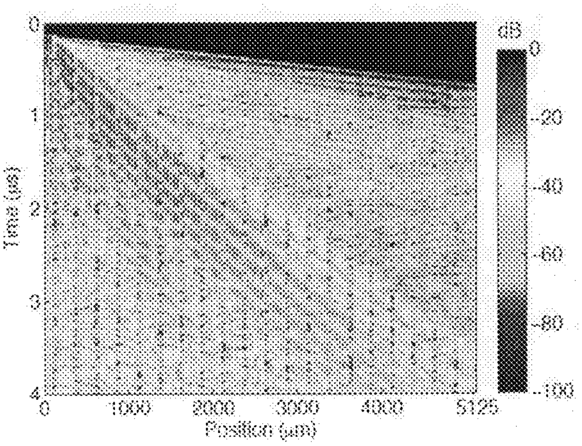
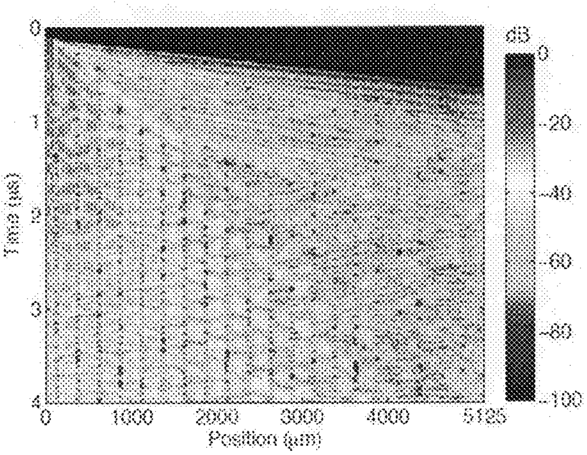
*Primary Examiner*—Walter Benson
*Assistant Examiner*—Karen B Addison
(74) *Attorney, Agent, or Firm*—Lumen Patent Firm

(57) **ABSTRACT**

A reduced crosstalk capacitive micromachined ultrasonic transducer (CMUT) array is provided. The CMUT array has at least two CMUT array elements deposited on a substrate, at least one CMUT cell in the array element, a separation region between adjacent CMUT array elements, and a membrane formed in the separation region. The membrane reduces crosstalk between adjacent array elements, where the crosstalk is a dispersive guided mode of an ultrasonic signal from the CMUT propagating in a fluid-solid interface of the CMUT array. Each cell has an insulation layer deposited to the substrate. A cell membrane layer is deposited to the insulation layer, where the cell membrane layer has a vacuum gap therein. The cells further have an electrode layer deposited to a portion of the membrane layer, and a passivation layer deposited to the electrode layer, the cell membrane layer and to the insulation layer.

**14 Claims, 9 Drawing Sheets**





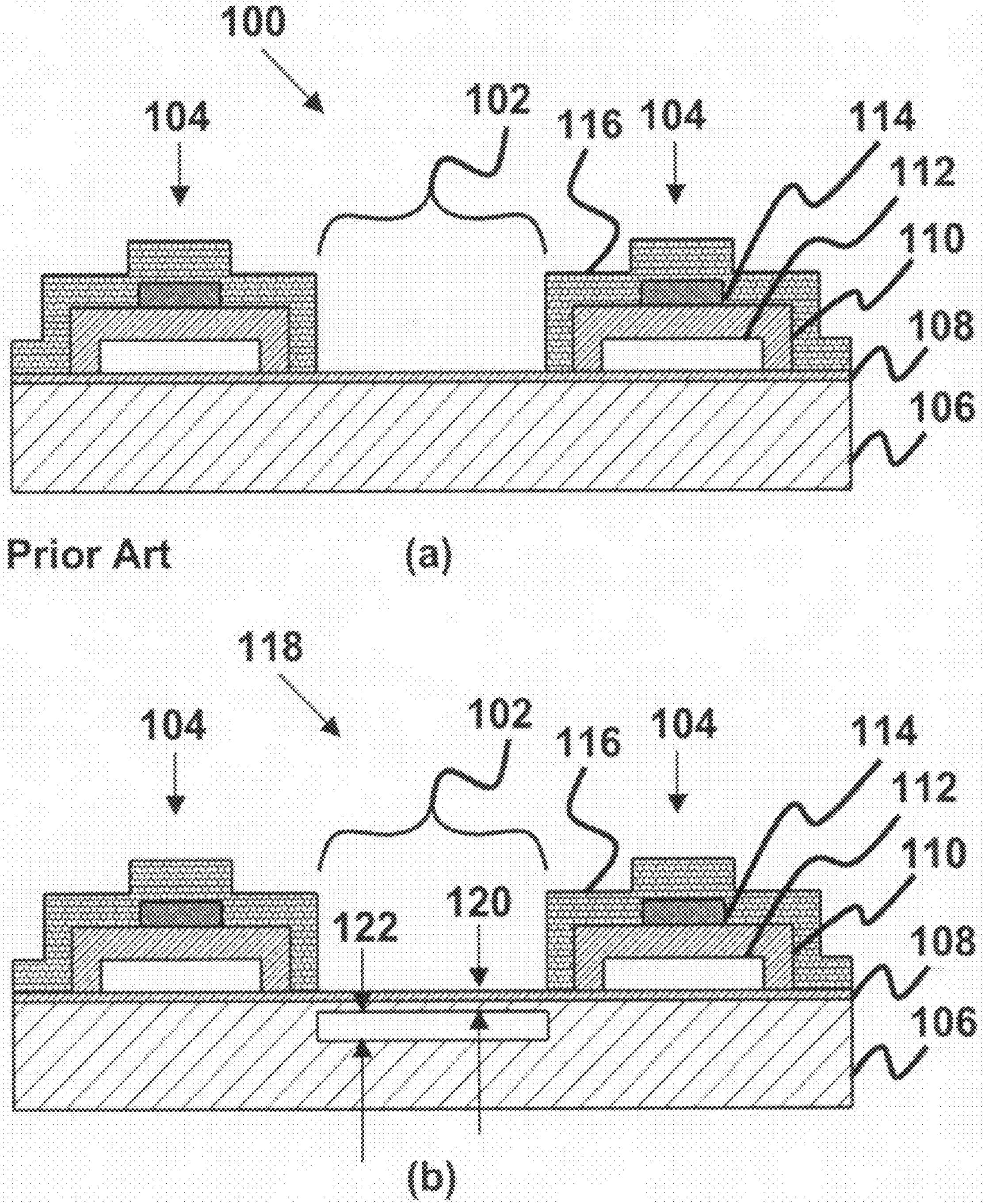
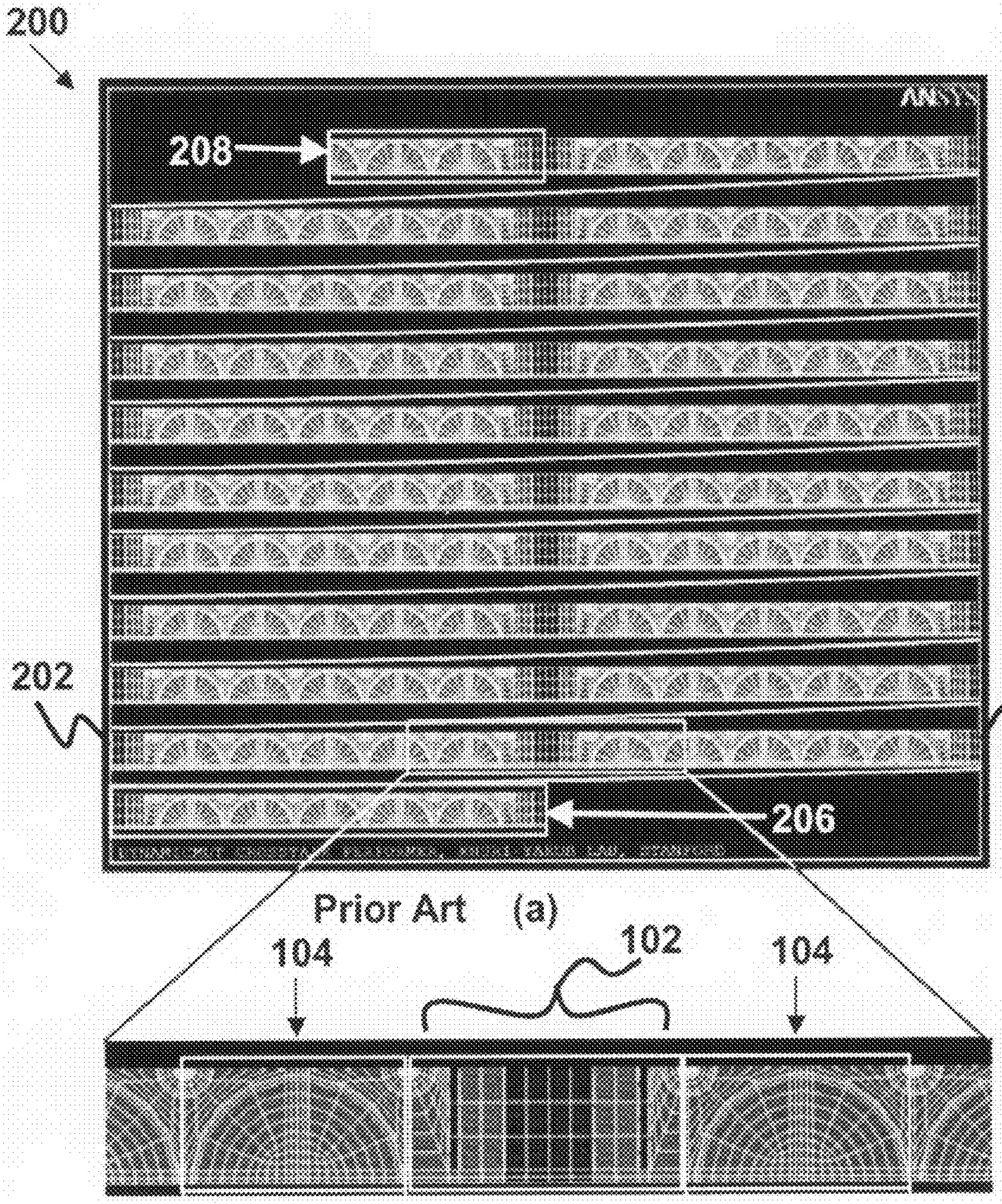

100
104
102
116
104
114
112
110
108
106
Prior Art
(a)
118
104
102
116
104
114
112
110
122
120
108
106
(b)

*FIG. 1*



Prior Art (a)

Prior Art (b)

FIG. 2

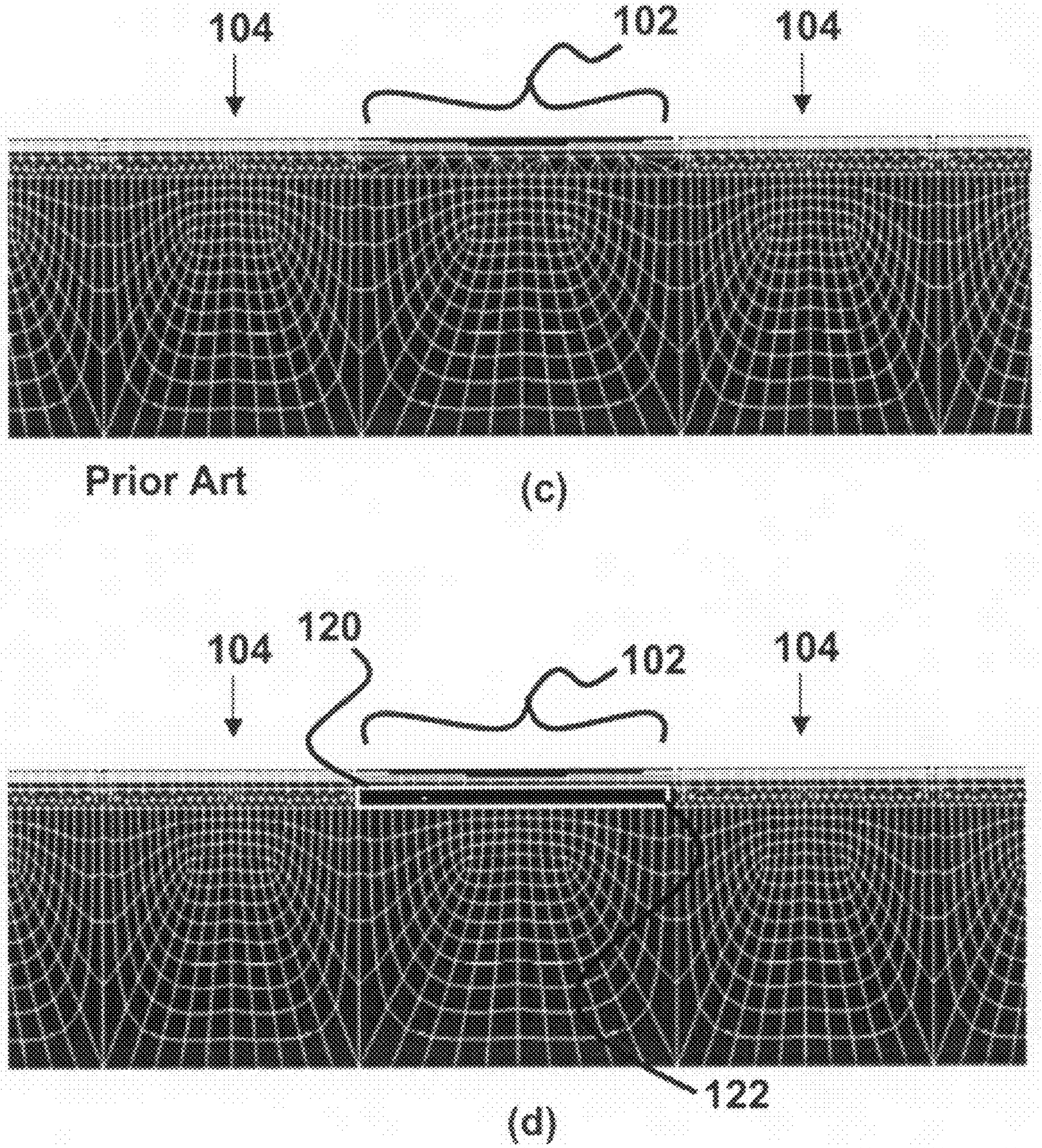


FIG. 2 cont.

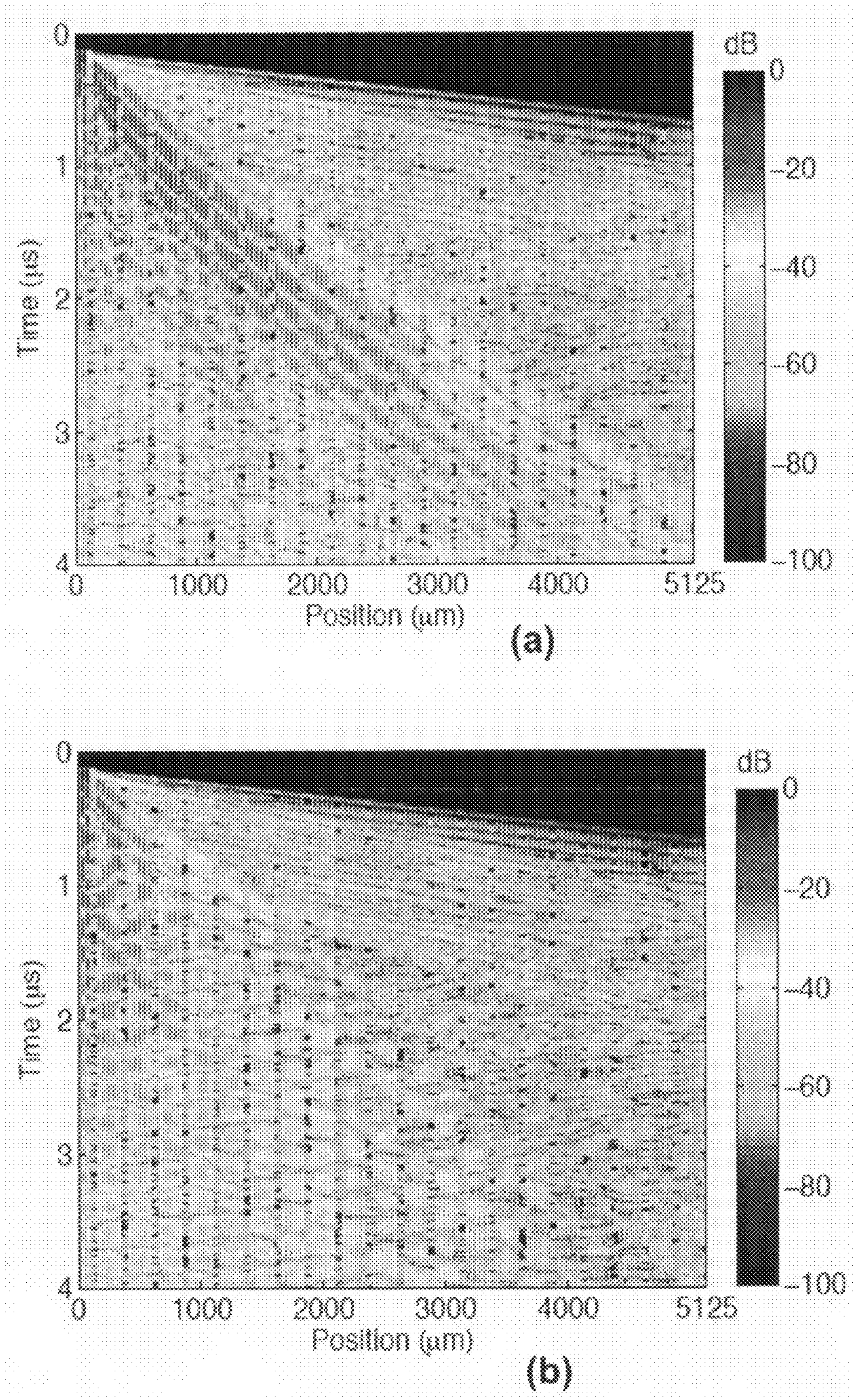
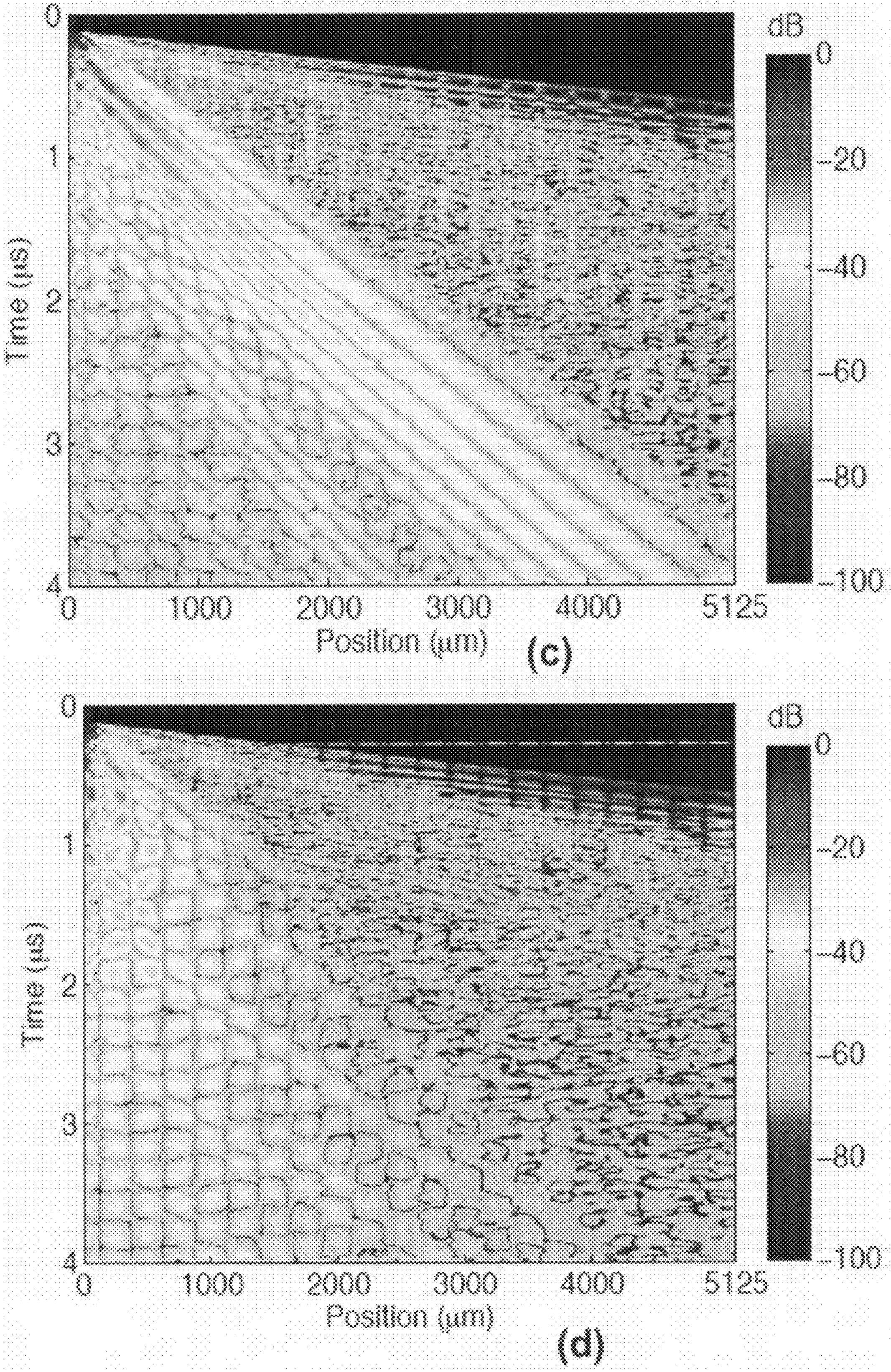

Time (µs)
0
1
2
3
4
Position (µm)
0
1000
2000
3000
4000
5125
dB
0
-20
-40
-60
-80
-100
(a)
Time (µs)
0
1
2
3
4
Position (µm)
0
1000
2000
3000
4000
5125
dB
0
-20
-40
-60
-80
-100
(b)

*FIG. 3*


0
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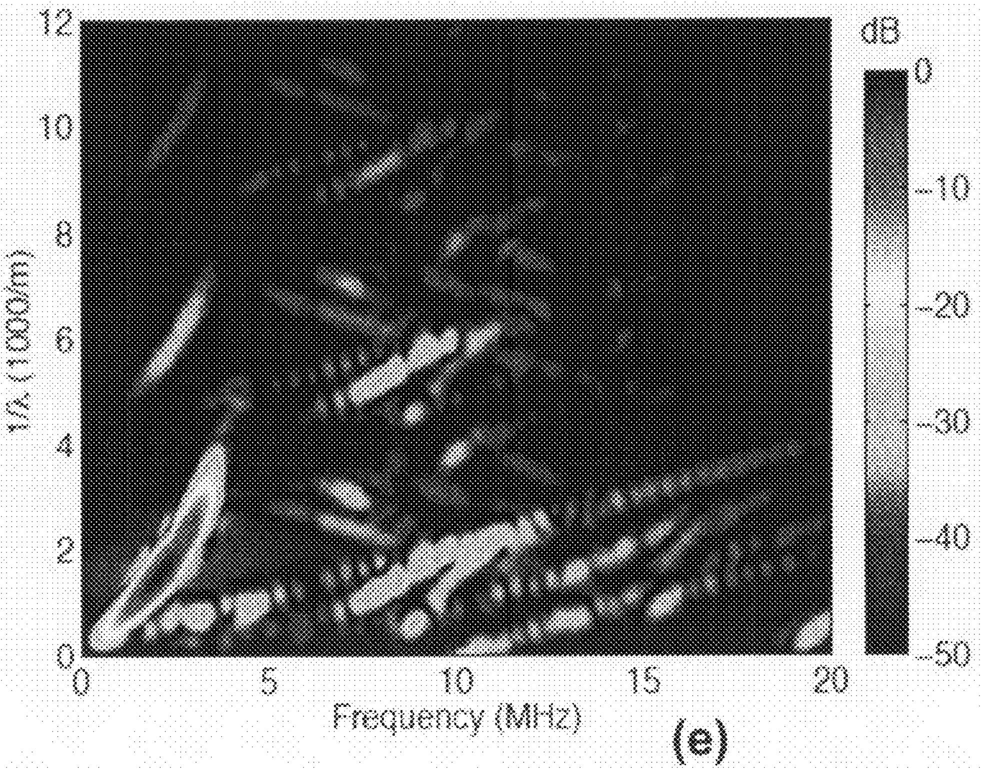
Time (µS)
0
1000
2000
3000
4000
5125
Position (µm)
dB
0
-20
-40
-60
-80
-100
(c)
0
1
2
3
4
Time (µS)
0
1000
2000
3000
4000
5125
Position (µm)
dB
0
-20
-40
-60
-80
-100
(d)

*FIG. 3 cont.*


12
10
8
6
4
2
0
1/λ (1000/m)
0
5
10
15
20
Frequency (MHz)
dB
0
−10
−20
−30
−40
−50
(e)

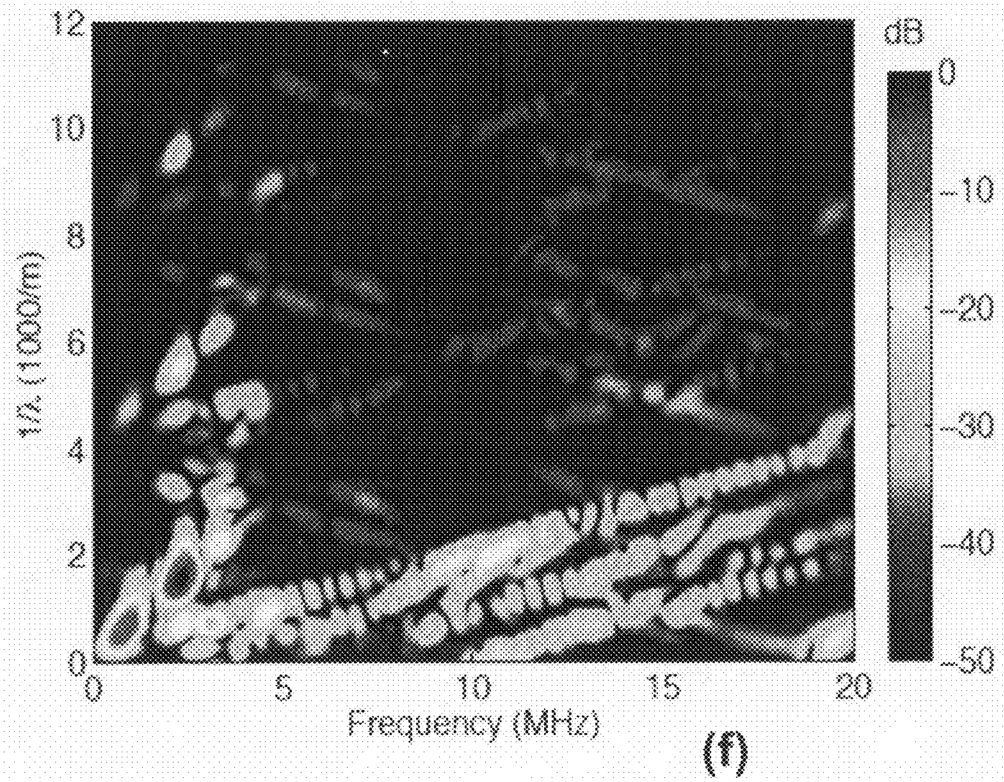
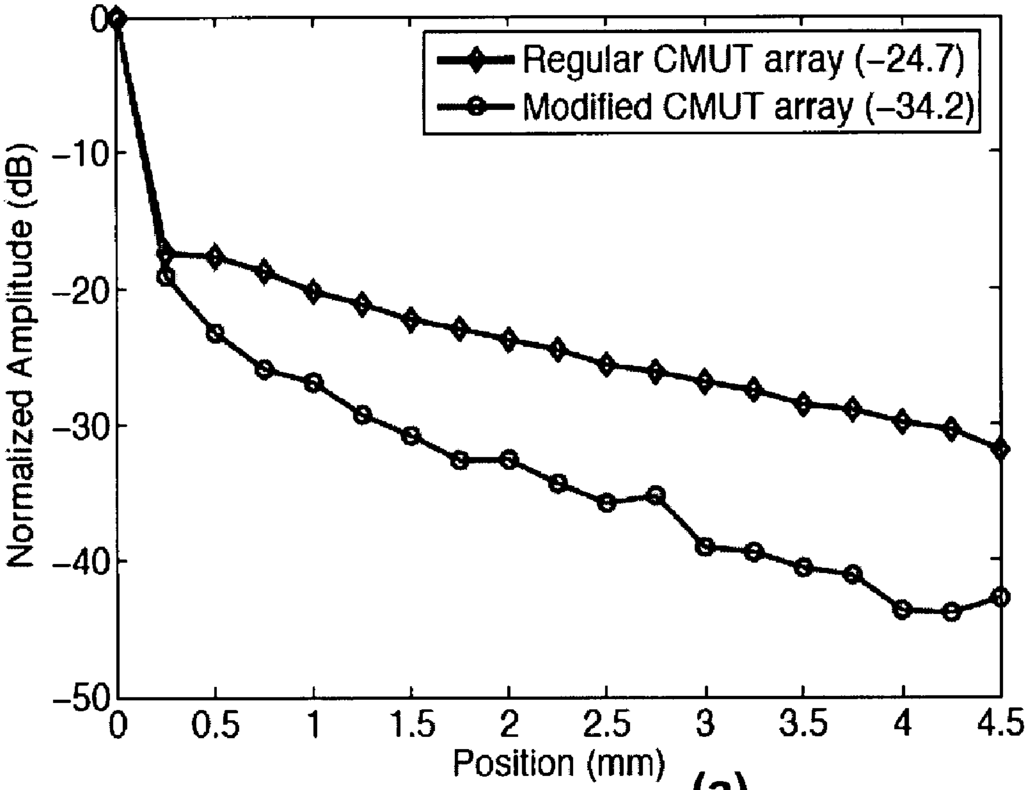
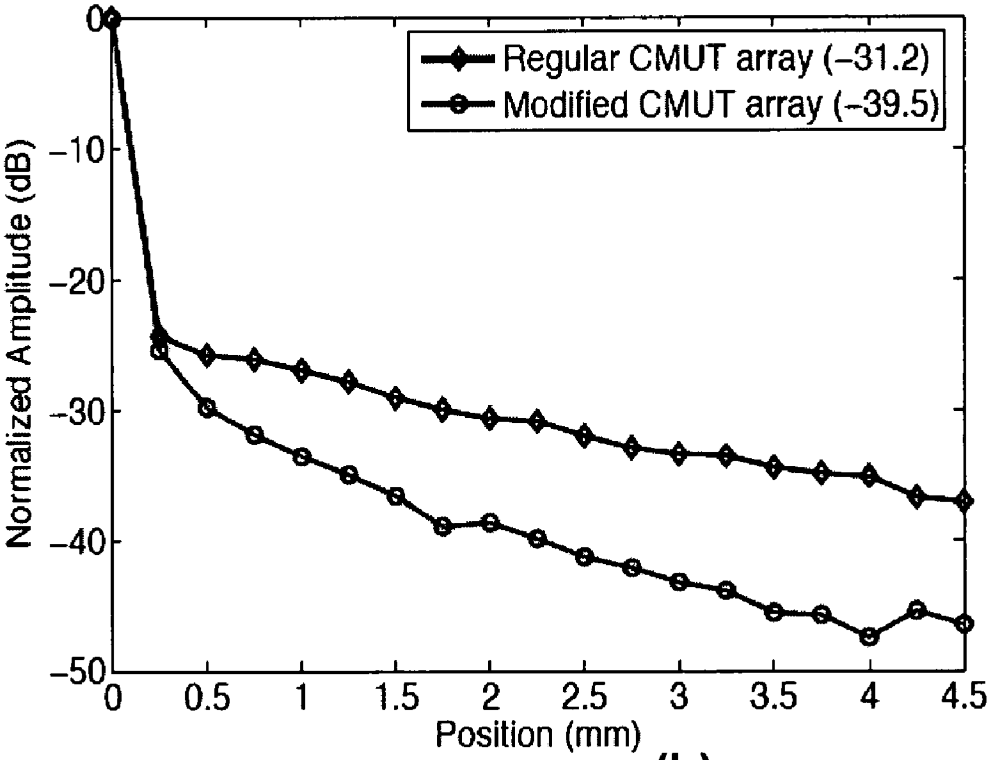

12
10
8
6
4
2
0
1/λ (1000/m)
0
5
10
15
20
Frequency (MHz)
dB
0
−10
−20
−30
−40
−50
(f)

*FIG. 3 cont.*


Regular CMUT array (−24.7)
Modified CMUT array (−34.2)
Normalized Amplitude (dB)
0
−10
−20
−30
−40
−50
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
Position (mm)

(a)


Regular CMUT array (−31.2)
Modified CMUT array (−39.5)
Normalized Amplitude (dB)
0
−10
−20
−30
−40
−50
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
Position (mm)

(b)

*FIG. 4*

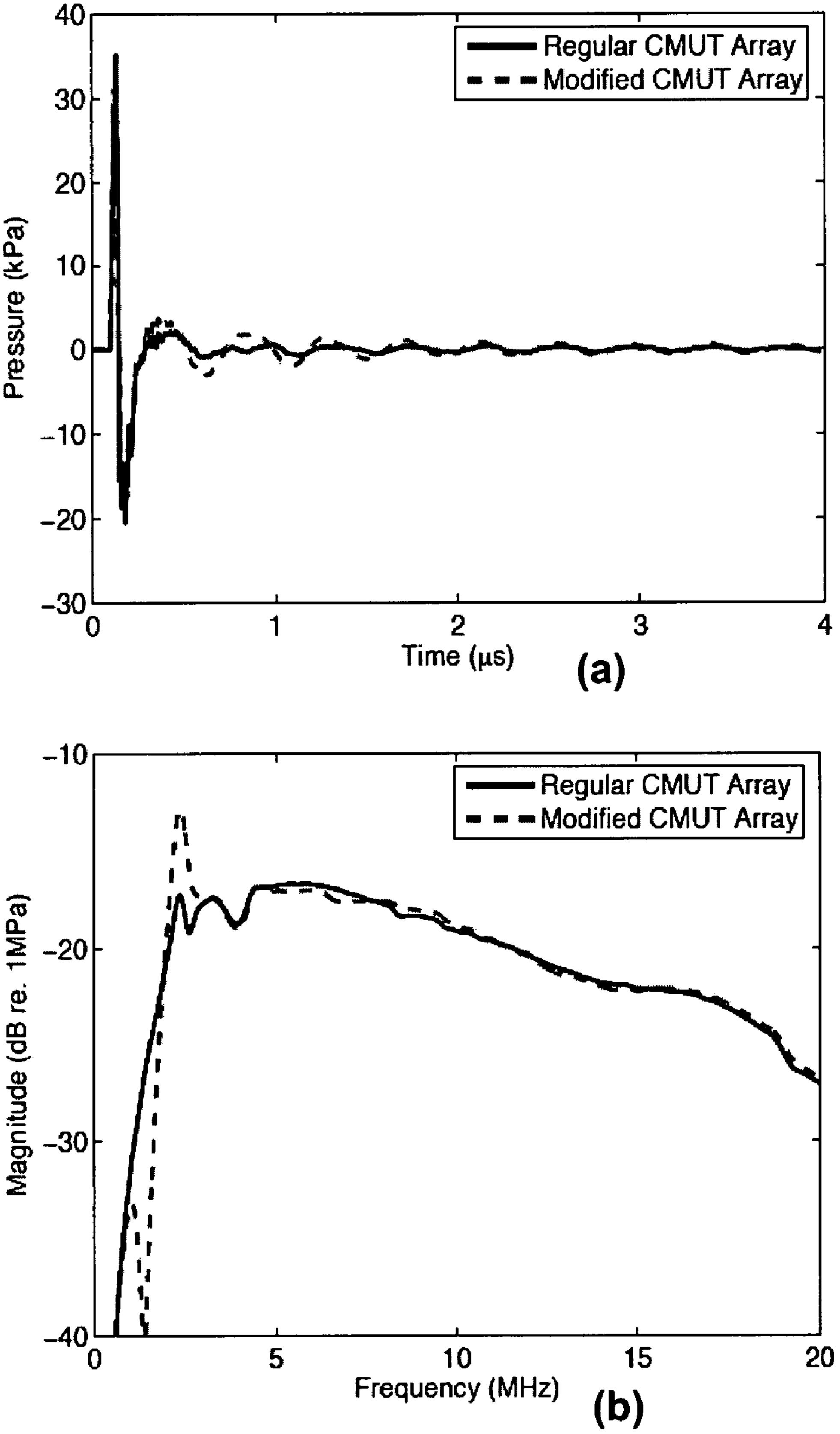

40
30
20
10
0
−10
−20
−30
Pressure (kPa)
0
1
2
3
4
Time (μs)
Regular CMUT Array
Modified CMUT Array
(a)
−10
−20
−30
−40
Magnitude (dB re. 1MPa)
0
5
10
15
20
Frequency (MHz)
Regular CMUT Array
Modified CMUT Array
(b)

*FIG. 5*

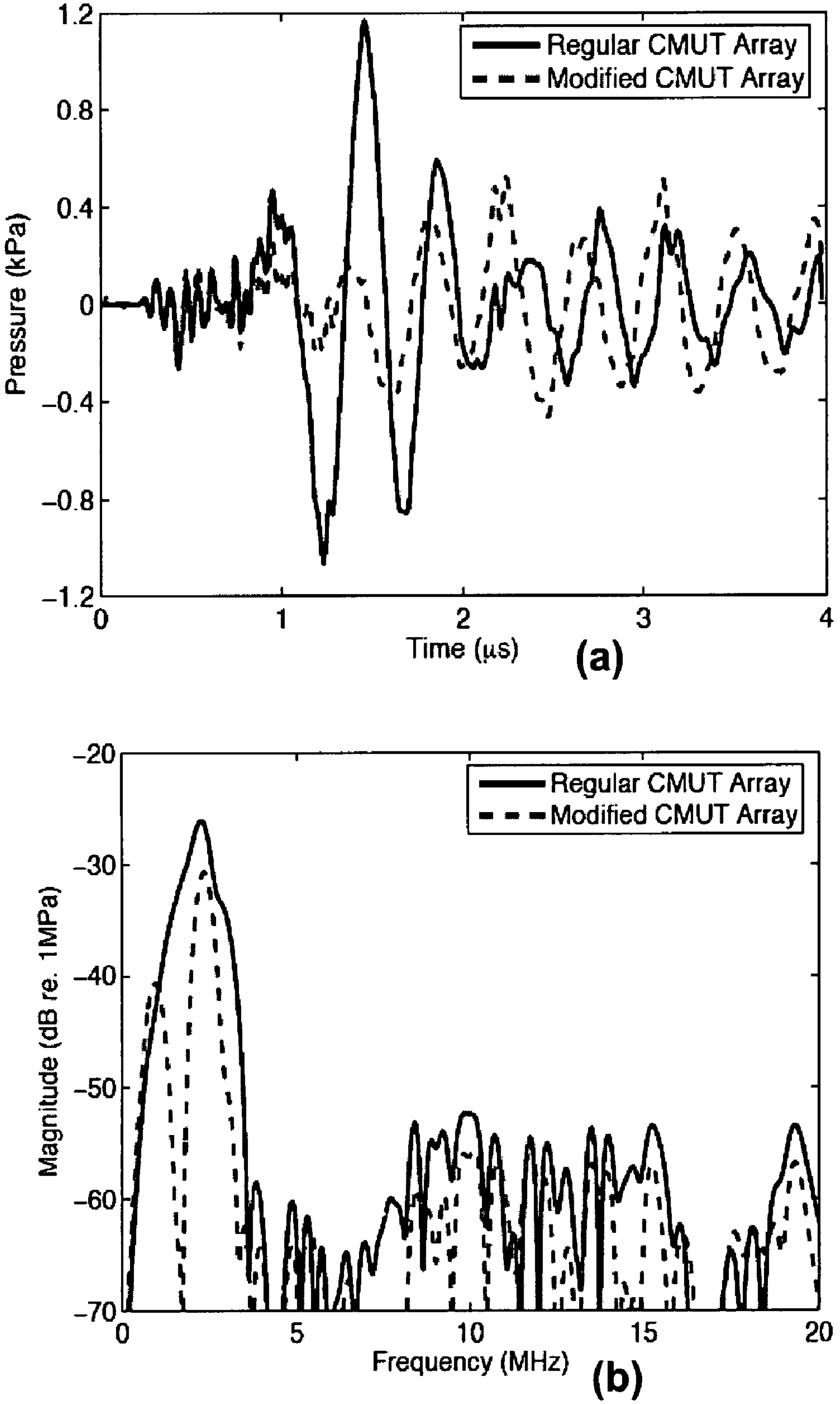

Regular CMUT Array
Modified CMUT Array
Pressure (kPa)
1.2
0.8
0.4
0
−0.4
−0.8
−1.2
0
1
2
3
4
Time (μs)
(a)
Regular CMUT Array
Modified CMUT Array
Magnitude (dB re. 1MPa)
−20
−30
−40
−50
−60
−70
0
5
10
15
20
Frequency (MHz)
(b)

*FIG. 6*

# ACOUSTIC CROSSTALK REDUCTION FOR CAPACITIVE MICROMACHINED ULTRASONIC TRANSDUCERS IN IMMERSION

## CROSS-REFERENCE TO RELATED APPLICATIONS

This application is cross-referenced to and claims the benefit from U.S. Provisional Patent Application 60/797,489 filed May 3, 2006 which is hereby incorporated by reference.

## STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH OR DEVELOPMENT

The present invention was supported in part by grant number HL67647 from the National Institute of Health, and supported in part by grant number N00014-02-1-0007 from the United States Office of Naval Research. The U.S. Government has certain rights in the invention.

## FIELD OF THE INVENTION

The invention relates generally to capacitive micromachined ultrasonic transducers (CMUTs). More particularly, the invention relates to apparatus and methods for reducing acoustic crosstalk between the elements of CMUT arrays in immersion by placing a membrane in the separation region between neighboring array elements.

## BACKGROUND

Microfabrication technology that employed the techniques originally developed for the integrated circuit (IC) industry has become popular in diverse areas of science and engineering to create miniaturized transducers. A transducer is a conduit for transforming energy between two or more domains such as mechanical, electrical, thermal, chemical and magnetic. Capacitive micromachined ultrasonic transducers (CMUTs) relate electrical and mechanical domains in energy transfer to transmit and receive ultrasound. As an alternative to piezoelectric transducers, CMUTs offer several advantages such as wide bandwidth, ease of large array fabrication and potential for integration with electronics. Parasitic energy coupling, or crosstalk, between neighboring elements has been observed in immersed operation. It has been determined that the main crosstalk mechanism is a dispersive guided mode propagating in the fluid-solid interface. This coupling degrades the performance of transducers in immersion for medical applications such as diagnostic imaging and high intensity focused ultrasound (HIFU) treatment.

Experimental, analytical and finite element methods have been used to understand the causes and effects of crosstalk in CMUTs. Attempts have been made to reduce the crosstalk, such as changing the substrate thickness and placing etched trenches or polymer walls between the array elements. These efforts were explored using finite element methods. These methods did not significantly affect the crosstalk observed to be −22 dB in immersion.

Another attempt, based on a mathematical CMUT model, covered the top of the array with a thin, lossy solid layer was found to damp out the unwanted resonances that occur on certain frequencies and steering angles due to the coupling in the acoustic medium. However the problem of reducing the dispersive guided mode of an ultrasonic signal remained unaddressed.

Accordingly, there is a need to develop a CMUT array that has reduced crosstalk between the neighboring array elements. There is a further need to improve transducer performance for applications such as diagnostic imaging and high intensity focused ultrasound (HIFU) treatment in medicine. A need exists to reduce the effective element aperture and the ringdown time of a transducer, and improve angular response and range resolution. Further, it would be considered an innovative step with CMUT arrays to improve the axial resolution and bright patterns in the near field.

## SUMMARY OF THE INVENTION

The present invention provides a reduced crosstalk capacitive micromachined ultrasonic transducer (CMUT) array. The CMUT array has at least two CMUT array elements deposited on a substrate, at least one CMUT cell in the array element, a separation region between adjacent CMUT array elements, and a membrane formed in the separation region. The membrane reduces crosstalk between the adjacent array elements, where the crosstalk is a dispersive guided mode of an ultrasonic signal from the CMUT propagating in a fluid-solid interface of the CMUT array.

In one aspect of the invention, all the separation regions between the elements are substantially the same, whereby forming a substantial periodicity of the CMUT elements within the CMUT array. In another aspect of the invention, the periodicity of the array elements is in one dimension, and in another aspect, the periodicity of the array elements is in two dimensions.

In another aspect of the invention, the separation regions are substantially the same, forming a substantial periodicity of the CMUT elements within the CMUT array. In yet another aspect, the CMUT cells within the elements are substantially the same, forming a substantial periodicity of the CMUT cells within the CMUT element.

In another aspect of the invention, the CMUT operates in a conventional mode or a collapsed mode to transmit and receive ultrasound.

In a further aspect of the invention, the CMUT cell has an insulation layer deposited to the substrate, a cell membrane layer deposited to the insulation layer, where the cell membrane layer has a gap therein. The CMUT cell further has an electrode layer deposited to the membrane layer, where the electrode layer covers a portion of said membrane layer, and a passivation layer. The passivation layer is deposited to the electrode layer, the cell membrane layer and to the insulation layer.

In one embodiment of the invention, the gap is a vacuum gap.

In another embodiment of the invention, the CMUT cell may have a geometry such as circular, square, hexagonal or tented.

In another aspect of the invention, the insulation layer may be made from silicon nitride or silicon oxide. In a further aspect the membrane layer may be made from silicon nitride or silicon oxide. In yet another aspect, the electrode layer may be made from aluminum or gold. In a further aspect, the passivation layer may be made from silicon nitride or silicon oxide.

## BRIEF DESCRIPTION OF THE FIGURES

The objectives and advantages of the present invention will be understood by reading the following detailed description in conjunction with the drawing, in which:

FIG. **1**(*a*) shows a planar cross-section view of the separation region between the closest cells of the neighboring array elements.

FIG. **1**(*b*) shows a planar cross-section view of the separation region between the closest cells of the neighboring array elements of a reduced crosstalk CMUT array (modified array) according to the present invention.

FIG. **2**(*a*) shows a top view of finite element model (FEM) of the 1-D CMUT array surface.

FIG. **2**(*b*) shows a magnified view of the top surface of the separation region and neighboring cells of Element 18 and Element 19 of FIG. **2**(*a*).

FIG. **2**(*c*) shows a side view of the separation region and the cells for a regular CMUT array: bulk substrate in the separation region.

FIG. **2**(*d*) shows side view of the separation region and the cells for a reduced crosstalk CMUT array (modified array): membrane formed in the separation region according to the current invention.

FIG. **3**(*a*) shows crosstalk waves of the regular CMUT arrays: displacement results in the time-spatial domain.

FIG. **3**(*b*) shows crosstalk waves of the reduced crosstalk CMUT array (modified array): displacement results in the time-spatial domain according to the current invention.

FIG. **3**(*c*) shows pressure results for the regular CMUT array in the time-spatial domain.

FIG. **3**(*d*) shows pressure results for the reduced crosstalk CMUT array (modified array) in the time-spatial domain according to the current invention.

FIG. **3**(*e*) shows pressure results for the regular CMUT array in the frequency-wavenumber domain.

FIG. **3**(*f*) shows pressure results for the reduced crosstalk CMUT array (modified array) in the frequency-wavenumber domain array according to the current invention.

FIG. **4**(*a*) shows crosstalk normalized amplitudes of array elements averaged over the array elements: displacement results for regular array and reduced crosstalk CMUT array (modified array).

FIG. **4**(*b*) shows crosstalk normalized amplitudes of array elements averaged over the array elements: pressure results for regular array and reduced crosstalk CMUT array (modified array).

FIG. **5**(*a*) shows acoustic output pressure of the transmitter element averaged over the transmitter element: time-spatial domain for regular array and reduced crosstalk CMUT array (modified array).

FIG. **5**(*b*) shows acoustic output pressure of the transmitter element averaged over the transmitter element: frequency-wavenumber domain for regular array and reduced crosstalk CMUT array (modified array).

FIG. **6**(*a*) shows acoustic crosstalk pressure on the $5^{th}$ neighboring element: time-spatial domain for regular array and reduced crosstalk CMUT array (modified array).

FIG. **6**(*b*) shows acoustic crosstalk pressure on the $5^{th}$ neighboring element: frequency-wavenumber domain for regular array and reduced crosstalk CMUT array (modified array).

## DETAILED DESCRIPTION OF THE INVENTION

Although the following detailed description contains many specifics for the purposes of illustration, anyone of ordinary skill in the art will readily appreciate that many variations and alterations to the following exemplary details are within the scope of the invention. Accordingly, the following preferred embodiment of the invention is set forth without any loss of generality to, and without imposing limitations upon, the claimed invention.

The premise of crosstalk reduction stems from several observations and how they relate to the current invention to reduce the crosstalk, the observations are as follows:

1) The main crosstalk mechanism is the dispersive guided mode (−23 dB) propagating in the fluid-solid interface compared to $A_0$ (−40 dB) and $S_0$ (−65 dB) Lamb Wave modes. The current invention reduces the crosstalk and impedes the propagation of this guided mode.
2) This guided mode disappears close to 4 MHz, corresponding to the membrane resonance in immersion. Although the 3-dB bandwidth of the transmitter array element extends from 2 MHz to 9.6 MHz, this guided mode is not observed above the cut-off frequency of 4 MHz. This result shows the strong influence of the membranes on top of the array elements to affect the spectra of the crosstalk.
3) This guided mode has the peak at 2.3 MHz with a narrowband. Therefore, by only impeding the propagation of the guided mode at a frequency in the vicinity of 2.3 MHz the crosstalk is sufficiently reduced.

From the second observation, the invention provides a periodic arrangement of a membrane between the array elements such that the propagation of the guided mode is impeded at a frequency close to the center frequency of the guided mode. FIG. **1**(*a*) shows a cross-section view of a prior art CMUT array **100**, where shown is a separation region **102** between the closest cells **104** of the neighboring array elements (see FIGS. **2**). The regular CMUT array **100** has a bulk substrate **106** in the separation region **102** between the elements (see FIGS. **2**). The CMUT cell **104** has an insulation layer **108** deposited to the substrate **106**, a cell membrane layer **110** deposited to the insulation layer, where the cell membrane layer has a gap **112** therein. The CMUT cell **104** further has an electrode layer deposited **114** to the membrane layer **110**, where the electrode layer **114** covers a portion of said membrane layer **110**, and a passivation layer **116**. The passivation layer **116** is deposited to the electrode layer **114**, the cell membrane layer **110** and to the insulation layer **108**.

FIG. **1**(*b*) shows a cross-section view of a reduced crosstalk CMUT array **118**, where a membrane **120** is formed in the separation region **102** according to the current invention by creating a vacuum gap **122** right below the membrane **120**. This modification does not affect the static behavior of the cells **104** (voltage-capacitance relation and the collapse voltage) in the elements. In this embodiment of the invention, FIG. **1**(*b*) shows each CMUT cell **104** having an insulation layer **108** deposited to the substrate **106**, where the insulation layer **108** may be a silicon nitride layer or a silicon oxide layer. Further shown is a cell membrane layer **110** deposited to the insulation layer **108**, where the cell membrane layer **110** has a gap **112** therein. The cell membrane layer **110** may be a silicon nitride layer or a silicon oxide layer. According to one embodiment of the invention, the gap **112** is a vacuum gap. The CMUT cells **104** further have an electrode layer deposited **114** to the membrane layer **110**, where the electrode layer **114** covers a portion of said membrane layer **110** and a passivation layer **116**. The electrode layer **114** may be made from aluminum or gold. The passivation layer **116** is deposited to the electrode layer **114**, the cell membrane layer **110** and to the insulation layer **108**, where the passivation layer may be a silicon nitride layer or a silicon oxide layer.

The current invention is based on a finite element analysis (FEA). Referring to FIGS. **2**(*a*)-**2**(*d*), shown is a finite element model (FEM) of the 1-D CMUT array. FIG. **2**(*a*) shows a top view of a one-half of a 41-element CMUT array **200** surface divided at the center symmetry plane. FIG. **2**(*b*) shows a magnified, top view of a separation region **102** and neighboring cells **104** of Element 18 **202** and Element 19 **204**. FIG. **2**(*c*) show a side view of the separation region **102** and the cells **104** for a regular CMUT array **200**, where shown is the bulk substrate **106** in the separation region **102**. FIG. **2**(*d*) shows a side view of the separation region **102** and the cells **104** for a reduced crosstalk CMUT array **118** having the membrane **120** formed in the separation region **102** by creating a vacuum gap **122** right below the membrane **120**.

FIG. **2**(*a*) shows a 3-D finite element model of a 1-D CMUT array that includes periodic array elements **206** on the surface of the substrate **106**, where shown are five cells **104** in each element **206**. Using the symmetries of the array, the CMUT model describes a CMUT array, 41-elements long in one dimension and infinite in the elevation direction, where FIG. **2**(*a*) shows half of the transmitter element **208** and 20 neighboring array elements **206** on one side of the transmitter element **208**. In the FEA model, the CMUT is immersed in soybean oil. The separation regions **102** between the elements **206** are substantially the same and form a substantial periodicity within the reduced crosstalk CMUT array **118**. This periodicity can be in one dimension or in two dimensions. Additionally, all the membranes **120** in the separation regions **102** are substantially the same and form a substantial periodicity of the CMUT elements **206** within the reduced crosstalk CMUT array **118**. Further, all the CMUT cells **104** within the elements **206** are substantially the same and form a substantial periodicity of the CMUT cells **104** within the CMUT elements **206**.

The excited element (or transmitter element) **208** is the central element **206** in the 41-element CMUT array, covered with 20 elements **206** on both sides. The element pitch is 250 μm and each element **206** includes 5 circular cells **104** with a diameter of 40 μm. Therefore, a separation region of 50 μm in length exists between the closest cells of the neighboring elements. The cells **104** are shown as circular-shapes, however it should be obvious that the cells **104** can be square, hexagonal or tent shaped, where the tent shaped cell membrane is supported at the center, but it is free on the edges. The top and side views of the separation region **102** between Element 18 **202** and Element 19 **204** are shown in FIG. **2**(*b*) and FIG. **2**(*c*), respectively. The regular CMUT array **100** has the substrate **106** in the separation region **102**. To model the reduced crosstalk CMUT array **118**, the regular CMUT array **100** is modified to have a membrane **120** in the separation region **102** (FIG. **2**(*d*)). The reduced crosstalk CMUT array **118** is identical to the regular array **100** in every aspect except the presence of a membrane **120** in each separation region **102**. A gap **122** (see FIG. **1** (*b*)) of 3 μm in height and 50 μm in length extends over the whole separation region **102** in the elevation direction. The membrane **120** (see FIG. **1**(*b*)) over the gap **122** is made of 1 μm silicon covered with 0.3 μm silicon nitride.

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 LSDYNA calculations. A DC voltage of 75 V was applied to all the elements **206** while operating in the conventional mode. Then a 20-ns, +10-V unipolar pulse was applied to the transmitter element **208**. The pulse amplitude and duration were selected such that the array elements did not accidentally operate in collapsed, or collapse-snapback modes. The displacement and the pressure over the whole array surface were collected with a time step of 10 ns for a total time of 4 μs. The simulation was performed using LS-DYNA executable (ver. 970-5434d) on a workstation (dual-processor 3 GHz Dell Precision 470, Dell Inc., Round Rock, Tex.) with a Linux operating system (GNU) for both regular and modified CMUT arrays. For transducers operated in the collapsed mode, the cell membrane **110** is first subjected to a voltage higher than the collapse voltage, therefore initially collapsing the membrane cell **110** onto the insulation layer **108** on the substrate **106**. Then, a bias voltage is applied having an amplitude between the collapse and snapback voltages. At this bias voltage, the center of the cell membrane **110** still contacts the insulation layer **108** on the substrate **106**. By applying driving AC voltage or voltage pulse, harmonic membrane motion is obtained in a circular ring concentric to the center of a circular cell **104**, for example. In this regime, between collapse and snapback, the CMUT has a higher eletromechanical coupling efficiency than it has when it is operated in the conventional pre-collapse mode.

The regular CMUT array **100** and reduced crosstalk CMUT array **118** are compared to show the effects of the crosstalk reduction. In the displacement of the regular CMUT array **100** presented in the time-spatial domain shown in FIG. **3**(*a*), three components of crosstalk propagating with different phase velocities and signal strengths are observed. The fastest crosstalk component is the weakest, with −65 dB displacement amplitude relative to the transmitter **208**, and corresponds to $S_0$ Lamb Wave mode. A slightly slower component ($A_0$ Lamb Wave mode) is observed at −40 dB level, and the slowest component is the strongest, at −23 dB. The main crosstalk mechanism is the dispersive guided mode propagating in the fluid-solid interface. The displacement results for the reduced crosstalk CMUT array **118**, shown in FIG. **3**(*b*), demonstrate that the dispersive guided mode is reduced in amplitude.

The components of crosstalk in the regular CMUT array **100** and reduced crosstalk in the modified CMUT array **118** are also observed in the pressure results in the time-spatial domain, shown in FIGS. **3**(*c*) and **3**(*d*).

Although the time-spatial domain representation provides insight about the nature of crosstalk, the identification of different wave types is difficult in this approach. Therefore, a transformation into the frequency-wavenumber domain is required to analyze propagating multi-mode signals. A hanning window is used to reduce the generation of the side lobes in the spectra.

The pressure results, presented in the frequency wavenumber domain, demonstrate the dispersive guided mode as the strongest component of the crosstalk for both regular CMUT array **100**, shown in FIG. **3**(*e*) and reduced crosstalk CMUT array **118** shown in FIG. **3**(*f*). Both results are normalized to their respective maxima. Although the transmitter element **208** has a center frequency of 5.8 MHz with more than 130% fractional bandwidth, the dispersive guided mode for the regular array **100** has a single peak at 2.3 MHz, and the crosstalk amplitude decays rapidly away from this frequency. However, this mode for the reduced crosstalk CMUT array **118** has two peaks at 0.85 MHz and 2.3 MHz, separated with a dip occurring at 1.44 MHz.

The crosstalk level, averaged over the array elements **206**, is calculated for the displacement results, shown in FIG. **4**(*a*) and the pressure results, shown in FIG. **4**(*b*). The crosstalk level is reduced approximately 10 dB for the reduced crosstalk CMUT array **118** compared to the regular array **100**.

Acoustic pressure of the transmitter element **208** for the regular array **100** and reduced crosstalk CMUT array **118** is compared in the time-spatial domain, shown in FIG. **5**(*a*). Peak-to-peak pressure of 55 kPa is achieved in both cases. This means that the acoustic output pressure of the transmitter element **208** is not degraded for the reduced crosstalk CMUT array **118**. An increase in the ringing of the transmitter element **208** is observed for the reduced crosstalk CMUT array **118**. The spectrum of the acoustic pressure in FIG. **5**(*b*) show that the frequency of the ringing is 2.3 MHz, which corresponds to the center frequency of the guided mode. A dip at 1.44 MHz is observed in the reduced crosstalk CMUT array **118**.

Acoustic crosstalk pressure on the $5^{th}$ neighboring element **206** for the regular array **100** and the reduced crosstalk CMUT array **118** is compared in the time spatial domain as shown in FIG. **6**(*a*). The reduced crosstalk CMUT array **118** has a lower peak-to-peak crosstalk pressure than the regular array **100**. The spectrum of the crosstalk pressure for the reduced crosstalk CMUT array **118** has a dip at 1.44 MHz compared to that for the regular array **100** having a single peak at 2.3 MHz as shown in FIG. **6**(*b*).

In the displacement result of FIG. **3**(*a*), the number of CMUT cells **104** in each element **206** can be easily identified to be 5 as expected because of the almost stationary posts. Although the displacement in the separation region **102** is much smaller than the displacement in the CMUT cells **104**, the wave propagates uninterruptedly regardless of the discontinuity of the displacement on the interface. The interface waves carry most of their energy in the fluid medium as pressure waves. The displacement results for the reduced crosstalk CMUT array **118**, shown in FIG. **3**(*b*), demonstrate the higher amplitude reduction of the dispersive guided mode. Another observation is the propagation of the crosstalk in both forward and reverse directions as a consequence of reflection at the separation region **102**. The guided mode for the regular array **100** is clearly visible over 20 neighboring elements **206** in FIG. **3**(*a*), whereas the mode for the reduced crosstalk CMUT array **118** becomes obscure over 6 elements **206**. Lamb Wave modes ($A_0$ and $S_0$) are negligibly affected by the modification in the separation region **102** because of the virtually unchanged substrate **106** thickness.

The continuity of the pressure across the cells **104** and the elements **206** of the array **100** in FIG. **3**(*c*) verifies the strong coupling of the energy in the acoustic medium. The number of cells **104** in each element **206** and the number of elements **206** across a propagation distance cannot be determined from the pressure results. The pressure results for the reduced crosstalk CMUT array **118** shown in FIG. **3**(*d*), confirm the higher amplitude reduction of the dispersive guided mode observed in the displacement results. The pressure which is close to zero in the separation region **102** acts to confine the guided mode within each array element **206** causing back and forth propagation, shown in FIG. **3**(*d*). The effectiveness of the reduced crosstalk CMUT array **118** is clearly observed when the pressure results from identical CMUT arrays **100** that only differ with a membrane **120** in the separation region **102** are compared to each other, as shown in FIG. **3**(*c*) and FIG. **3**(*d*).

The physical meaning of the dip observed in FIG. **3**(*f*) is that the crosstalk wave at a frequency of 1.44 MHz is not allowed to propagate across the array elements **206**. The membrane **120** in the separation region **102** causes this dip and reduces the crosstalk. Lamb Wave modes, though more or less the same for both regular array **100** and reduced crosstalk CMUT array **118**, are more apparent for the reduced crosstalk CMUT array **118** as shown in FIG. **3**(*f*). The crosstalk level of the dispersive guided mode is approximately 10 dB smaller for the reduced crosstalk CMUT array **118**. Additionally, the multiples of the guided mode, separated by 4 $mm^{-1}$ along the wavenumber at 2.3 MHz, has a higher amplitude in the reduced crosstalk CMUT array **118** than in the regular array **100**. The amplitude of this multiple represents the discontinuity of the pressure, and higher amplitude means crosstalk reduction.

The crosstalk displacement and pressure are compared for both regular array **100** and the reduced crosstalk CMUT array **118** in the time-spatial domain as shown in FIGS. **3**(*a, b, c,* and *d*). Analyzing the pressure of the regular array **100** in the frequency-wavenumber domain reveals that the dispersive guided mode is narrowband at a center frequency of 2.3 MHz. On the other hand, the acoustic pressure of the excited element **208** is broadband at a center frequency of 5.8 MHz. This discrepancy is related to the different phase conditions in transmission and reception. During transmission, 5 cells **104** of the excited element **208** are all pulsed in phase, as shown in FIG. **3**(*c*). In-phase excitation causes higher center frequency and bandwidth for the transmitter element **208** than the center frequency and bandwidth of each individual cell **104**. The cells **104** of the neighboring element **206** pick up the crosstalk waves sequentially along the interface FIG. **3**(*c*). The phase delay between the cells **104** of an element **206** results in a lower center frequency (2.3 MHz) and bandwidth. The arrangement of the membranes **120** within the array element **206** influences the preferred frequency of the guided mode as a result of the phase delay between the adjacent cells **104**. The stiffness and density of the membrane **120** also determine the phase velocity of the guided mode.

The narrowband of the guided mode and the cut-off frequency of the membrane **120** in the separation region **102** make this invention rewarding in better crosstalk performance FIG. **4**. If the cut-off frequency of the membrane **120** falls outside the band of the guided mode, the reduced crosstalk CMUT array **118** will have negligible crosstalk improvement. To achieve higher amplitude reduction, the cut-off frequency of the membrane **120** should be even closer to the center frequency of the guided mode. However, this might increase the ringing of the transmitter element **208** and reduce the peak-to-peak acoustic pressure. Therefore, the membrane **120** is designed carefully to reduce the crosstalk without loss of the transmitter **208** output pressure using finite element methods.

An increase in the ringing of the transmitter element **208** is observed for the reduced crosstalk CMUT array **118** as a result of the reflections at the separation region **102**. A possible solution to this problem is changing the direction of the reflected crosstalk waves to propagate in the elevation direction along the separation region **102** between the array elements **206**, which will eliminate the ringing of the transmitter element **208**.

Using the verified LS-DYNA model, a novel reduced crosstalk CMUT array **118** is provided to reduce the amplitude of the dispersive guided mode propagating in the fluid-solid interface. This invention reduces the crosstalk level from −23 dB to −33 dB without loss of the acoustic pressure of the transmitter element **208**. The reduced crosstalk CMUT array **118** can be easily used for 1-D and 2-D CMUT arrays fabricated with surface micromachining or wafer-bonding to achieve superior crosstalk performance.

The present invention has now been described in accordance with several exemplary embodiments, which are intended to be illustrative in all aspects, rather than restrictive. Thus, the present invention is capable of many variations in detailed implementation, which may be derived from the description contained herein by a person of ordinary skill in the art. For example the membrane **120** in the separation region **102** can be designed as a circular, square, hexagonal and tented shape. The membrane **120** can also be designed with electrical connections so that the membrane **120** can be deflected or collapsed on the substrate. Higher DC voltage will increase the contact radius and increase the center frequency of the membrane **120**. Therefore, additional flexibility to tune this center frequency can be employed to adjust the crosstalk reduction efficiency. This will be particularly useful if the crosstalk wants to be reduced not only in conventional but also collapsed mode of operation. In our current example, if the crosstalk reduction wants to be employed in collapsed mode, 1 μm Si layer thickness should be increased to 1.4 μm to increase the center frequency of the membrane to account for the increase in the frequency of the dispersive guided mode.

All such variations are considered to be within the scope and spirit of the present invention as defined by the following claims and their legal equivalents.

What is claimed is:

**1**. A reduced crosstalk capacitive micromachined ultrasonic transducer (CMUT) array comprising:

a. at least two CMUT array elements deposited on a substrate;

b. at least one CMUT cell in said array element;

c. a separation region between adjacent said CMUT array elements; and

d. a membrane formed in said separation region, whereby said membrane reduces crosstalk between said adjacent array elements, whereas said crosstalk comprises a dispersive guided mode of an ultrasonic signal from said CMUT propagating in a fluid-solid interface of said CMUT array.

**2**. The CMUT array of claim **1**, wherein all said separation regions between said elements are substantially the same, whereby forming a substantial periodicity of said CMUT elements within said CMUT array.

**3**. The CMUT array of claim **2**, wherein said periodicity of said array elements is in one dimension.

**4**. The CMUT array of claim **2**, wherein said periodicity of said array elements is in two dimensions.

**5**. The CMUT array of claim **1**, wherein all said membranes in said separation regions are substantially the same, whereby forming a substantial periodicity of said CMUT elements within said CMUT array.

**6**. The CMUT array of claim **1**, wherein all said CMUT cells within said elements are substantially the same, whereby forming a substantial periodicity of said CMUT cells within said CMUT element.

**7**. The CMUT array of claim **1**, wherein said CMUT operates in a conventional mode or a collapsed mode to transmit and receive ultrasound.

**8**. The CMUT array of claim **1**, wherein said CMUT cell comprises:

a. an insulation layer deposited to said substrate;

b. a cell membrane layer deposited to said insulation layer, wherein said cell membrane layer has a gap therein;

c. an electrode layer deposited to said membrane layer, wherein said electrode layer covers a portion of said membrane layer; and

d. a passivation layer, wherein said passivation layer is deposited to;

  i. said electrode layer;
  ii. said cell membrane layer; and
  iii. said insulation layer.

**9**. The CMUT array of claim **8**, wherein said CMUT cell has a geometry selected from a group consisting of circular, square, hexagonal and tented.

**10**. The CMUT array of claim **8**, wherein said insulation layer is a layer selected from a group consisting of silicon nitride and silicon oxide.

**11**. The CMUT array of claim **8**, wherein said membrane layer is a layer selected from a group consisting of silicon nitride and silicon oxide.

**12**. The CMUT array of claim **8**, wherein said electrode layer is a layer selected from a group consisting of aluminum and gold.

**13**. The CMUT array of claim **8**, wherein said passivation layer is a layer selected from a group consisting of silicon nitride and silicon oxide.

**14**. The CMUT array of claim **8**, wherein said gap is a vacuum gap.

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