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Procedia Engineering 47 (2012) 542 – 545

Procedia Engineering

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Proc. Eurosensors XXVI, September 9-12, 2012, Kraków, Poland

Capacitive Micromachined Ultrasonic Transducer Array with Pencil Beam Shape and Wide Range Beam Steering

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Abstract

A capacitive micromachined ultrasonic transducer (CMUT) array is designed as an alternative to conventional piezoelectric transducers. A thin silicon nitride membrane is suspended over a bottom electrode on a silicon wafer. In the immersion mode, the transducer cell shape and dimensions are optimized for an operating frequency of 10MHz. We show that the proposed imager array can generate a pencil shape beam with a ~1.5° half beam width, enhancing the detector resolution. A phased array technique is employed to excite multiple cells using time-delayed signals to steer the acoustic beam toward the object. This eliminates the need to mechanically move the detector, simplifying the transducer driving system. Moreover, unlike conventional transducers, the pencil beam can be effectively steered over a wide range of angles without producing grating lobes, which minimizes power loss in undesired directions. This can also improve the signal to noise ratio of the imager CMUT array.

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Keywords: 1D transducer array; beam steering; capacitive micromachined ultrasonic transducer (CMUT); grating lobe; half beam width angle; phased array technique.

Nomenclature

N	number of CMUT cells in a 1-D array
θ	transducer beam steering angle
Δθ	beam width angle measured at -6dB of generated sound pressure level

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doi:10.1016/j.proeng.2012.09.204

1. Introduction

Piezoelectric transducers have commercially been used for detecting and imaging of various objects [1], such as water-trees in underground cables [2]. However, they are known to have several drawbacks, e.g. poor acoustic matching, dimensional limit [3]. In the past decade, CMUTs have been introduced as an alternative for piezoelectric transducers. They can be fabricated using microelectromechanical systems (MEMS) techniques with a sacrificial layer [4] or fusion bonding technologies [5]. Employing MEMS technology, CMUTs can be fabricated in different size and shapes. Therefore, the operational frequency can be varied over a wide range. Moreover, by utilizing phased array techniques, cells can be fired in different sequences, resulting in acoustic beam steering without physically moving the transducer array.

2. Capacitive Micromachined Transducer Array

In this paper, a CMUT array is proposed where COMSOL simulations have been used to optimize the cell shapes and dimensions for an operating frequency of f=10MHz. A schematic view of the proposed circular cell, employing a 30µm diameter membrane suspended over a bottom electrode, is shown in Fig. 1(a). The membrane is a 0.5µm thin silicon nitride film that creates a low stiffness, vibrating platform. The cavity is vacuum-sealed with a height of 0.6µm. A 0.15µm thin silicon nitride on the bottom electrode is used to avoid contact between the membrane and the substrate while the device operates close to the resonant frequency.

COMSOL electromechanical simulations have been performed to optimize the device structure as well as the bias voltage to generate the maximum deflection in the nitride membrane. The membrane is circular shape and is fixed at the edges. The first two natural frequencies of this structure are 9.9MHz and 20.2MHz, respectively. A 15V AC with a 135V DC bias voltage causes a maximum membrane vibration of U=38nm peak-peak, generating an acoustic signal in the water domain. Figs. 1(b) and 1(c) illustrate the membrane displacement map of an individual cell at these first two natural frequencies.

3. Acoustic Beam Properties

Several CMUT linear arrays, with different numbers of cells in the row, with a total aperture length of 2.5mm were investigated. To satisfy the beam uniformity requirement for detection, the sound pressure was simulated at 3cm from the center of the array, which maintains the far field condition. A pencil shape beam can be achieved by exciting all the individual cells simultaneously, enhancing the detector focusing and performance.

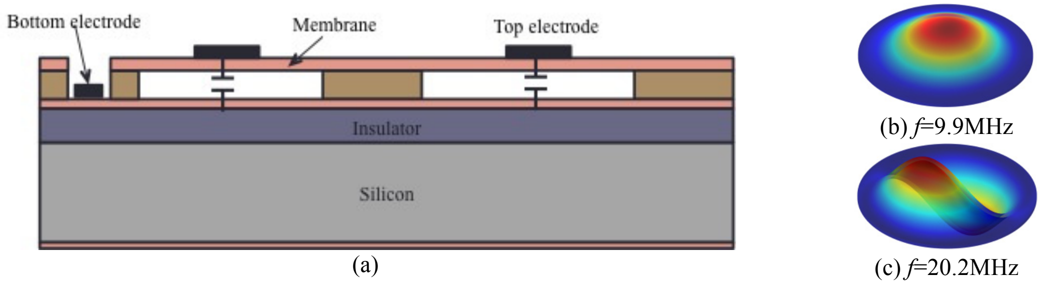
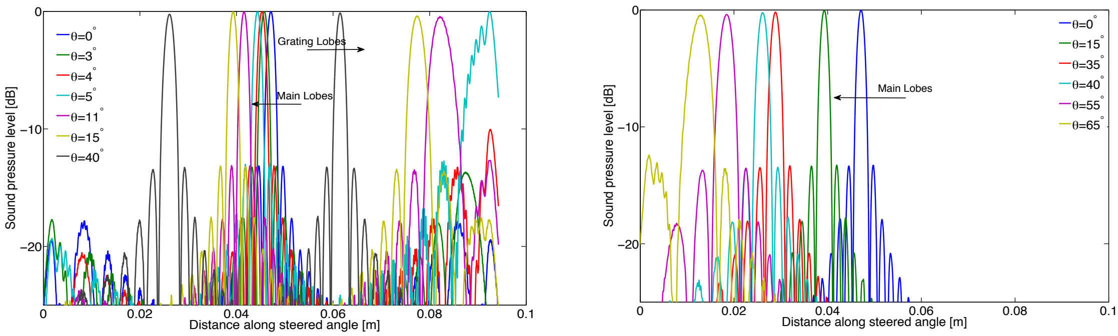


Fig. 1. a) Schematic view of a capacitive micromachined ultrasound transducer, CMUT, on silicon substrate, and the membrane displacement (U) map of an individual cell with 30µm diameter at the first two natural frequencies of a) 9.9MHz and b) 20.2MHz. The membrane is fixed at the edge (U=0, blue) and has the maximum displacement at the center (red).

Employing phased array technique in a homogeneous and isotropic acoustic medium, an inter-element phase shift in the CMUT applied voltage results in ultrasound beam steering [6]. However, one major concern in the transducer array is to avoid generating a grating lobe (GB) when the acoustic beam is steered [7]. Different methods have been proposed to avoid GBs, usually with a limited maximum angle of ~15° [8]. In this work, it is shown that with a dense array, GBs can be avoided and a steering angle as high as 65° can be achieved. In Figs. 2(a) and 2(b) the results for arrays with N=19 and N=81 cells are presented, where no GB is seen going for the denser array. At a steering angle of 15°, more than 29 elements are required to eliminate GBs, Fig. 3(a). For a θ=15° beam steering, the phase shift, from one end of the array to the other, are 84° and 19° for the arrays with N=19 and N=81 cells, respectively. In addition, a denser array results in a higher generated acoustic power, Fig 3(b), which in return enhances the transducer performances. The beam width increases at higher steering angles and Fig 4, illustrates that the half beam width angle increases from 1.5° to 4.5° when beam is steered toward θ=65°.

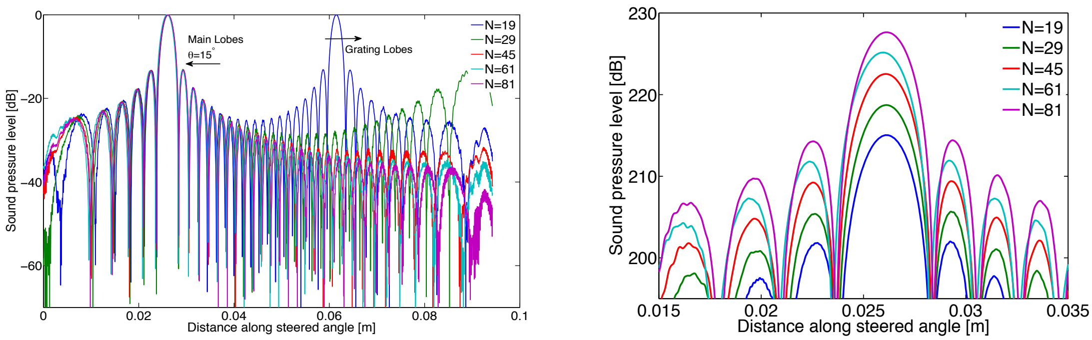
4. Conclusion

The directivity patterns of various 1-D CMUT arrays have been investigated using COMSOL acoustic simulations.



a) CMUT array with N=19 elements in a row b) CMUT array with N=81 elements in a row

Fig. 2. Sound pressure level generated along steering angle at the far field for the 9.8MHz capacitive micromachined transducer array with a) N=19 elements in a row. The transducer beam is steered at an angle of θ=0°, 3°, 4°, 5°, 11°, 15°, and 40°, respectively and b) N=81 elements in a row. The transducer beam is steered at an angle of θ=0°, 15°, 35°, 40°, 55°, and 65°, respectively.



(a) (b)

Fig. 3. Comparison of beam patterns at the far field of linear transducer arrays a) with a beam steering angle of θ=15° and b) θ=40°. Results are presented for arrays with N=19, 29, 45, 61, and 81 cells with a 30μm diameter and total array length of 2.5mm at 9.8MHz operation frequency.

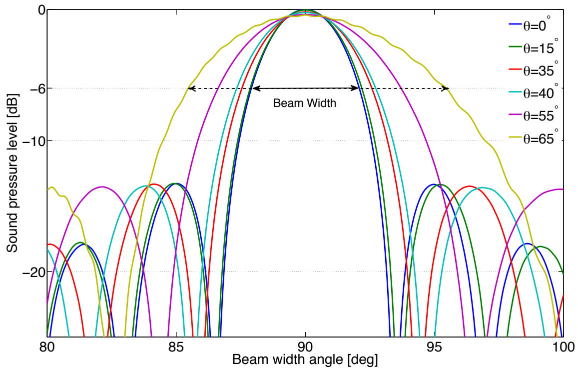


Fig. 4. Directivity pattern at the far field on a logarithmic scale of the 9.8MHz capacitive micromachined transducer array with 81 elements in a row. The generated beam is steered at an angle of θ=0°, 15°, 35°, 40°, 55°, and 65°, respectively. For comparison, the generated beams are plotted at the center angle of 90°, by a –θ shift in beam patterns. Beam width is measured at –6dB of sound pressure level.

Transducers shapes, dimensions as well as operating frequency have been chosen to optimize the membrane acceleration and hence the generated acoustic power for higher imaging resolution. It has been shown that the generated sound pressure level at the far-field distance, as well as the beam width, depend upon the number of CMUTs in each array. These results indicate that, while arrays with a higher number of CMUTs generates a higher power, their beam patterns are more directional. Moreover, in denser arrays the presence of grating lobes is eliminated and wider beam steering angles can be achieved.

Acknowledgements

The authors acknowledge the financial support by the Natural Sciences and Engineering Research Council of Canada (NSERC), and Manitoba Hydro. CMC Microsystems Canada is acknowledged for their COMSOL simulation support.

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