

ELECTRICALLY UNBIASED AND HALF
FREQUENCY DRIVEN WATERBORNE
16×16-ELEMENT 2-D PHASED ARRAY
CMUT

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By

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Electrically Unbiased and Half Frequency Driven Waterborne
16×16-Element 2-D Phased Array CMUT

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We certify that we have read this thesis and that in our opinion it is fully adequate,
in scope and in quality, as a thesis for the degree of Master of Science.

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ABSTRACT

**ELECTRICALLY UNBIASED AND HALF FREQUENCY
DRIVEN WATERBORNE 16x16-ELEMENT 2-D
PHASED ARRAY CMUT**

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Capacitive micromachined ultrasonic transducers (CMUT) are typically used as arrays consisting of separate cells or interconnected sub arrays, and these cells have several operation modes. Design procedure and measurements have been previously presented for an airborne CMUT cell without a DC bias. In unbiased mode, the plate motion spans the entire gap without collapsing. The frequency of sinusoidal electrical input signal is half of the resulting acoustical output signal. A large plate swing can be obtained at low excitation voltages using the entire remaining gap. In this work, a design procedure of arrays with unbiased operation mode is derived. Designs are validated by means of simulations and measurements on fabricated CMUTs. The problems associated with beamforming are resolved. Use of this operation mode in an array configuration enables larger acoustical power output. A better transmitted signal waveform definition is obtained when pulse width modulation (PWM) is employed.

In the design process of CMUTs, large-signal equivalent circuit model is used. In order to have volumetric transmission, a 16x16 (256 elements) phased array configuration is chosen. A design procedure is presented considering the radiation pattern, Rayleigh distance and the parameters of the lumped-element model. This procedure is applied for designing two arrays, with resonance

frequencies at 7.5 MHz and at 18.5 MHz. Harmonic balance and transient analyses are carried out with Gaussian enveloped tone burst, transient sinusoidal and PWM signals with different duty cycles. Outputs of these simulations are fed in beamforming toolboxes for further verification. Corresponding experimental measurements are conducted on an ultrasound measurement system.

The dimensions of the CMUT elements in the array are determined as 80 μm element radius, 15 μm plate thickness, and 171 nm effective gap height at 7.5 MHz, where the center-to-center inter-element pitch is set at 192 μm . The array is designed such that it has maximum Rayleigh distance of 45.3 mm, while having a maximum sidelobe level of -17.4 dB. According to these specifications, CMUT array is manufactured using wafer scale batch compatible production. Only two lithography masks, which require conventional photolithography steps, are used in production. The vibrating plate is constructed with anodic wafer bonding and the fabricated CMUT array chip is integrated to PCB with flip-chip bonding.

Measurements are conducted for this novel device by integrating the CMUT array chip manufactured with MEMS techniques and conventional macro scale manufactured PCB by using impedance analyser.

Keywords: Capacitive Micromachined Ultrasonic Transducers, CMUT, MEMS, Array, Unbiased Operation, Half Frequency Driven, Mutual Radiation Impedance, Waterborne, Volumetric Transmission, Large Signal Equivalent Circuit Model

ÖZET

BESLEMESİZ VE YARI FREKANSTA SÜRÜLEN SUALTI 16x16-ELEMANLI 2-B FAZLI DİZİN CMUT

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Kapasitif mikroişlenmiş ultrasonic çeviriciler (CMUT), genellikle ayrı elemanlar veya birbirine bağlı alt dizinler halinde, farklı çalışma modlarıyla kullanılmaktadır. Daha önce doğru akım (DA) kullanılmayan, havada çalışan, CMUT elemanı için tasarım prosedürü ve ölçümleri sunulmuştur. DA olmayan çalışma modunda CMUT membrane çökme olmadan, alt taş ile arasındaki boşluğun tamamını salınım için kullanabilmektedir. Elde edilen akustik çıkıştaki sinyalin frekansı, elektriksel girişteki sinusoidal alternatif akım sinyalin iki katıdır. Düşük sürme voltajlarında büyük membrane salınımları elde edilebilmektedir. Bu çalışmada, DA kullanılmayan CMUT dizinlerinin tasarım prosedürleri sunulmuştur. Tasarımlar simülasyonlar ve üretilen CMUT dizinleri ile yapılan deneylerle doğrulanmıştır. Hüzmelemeye ilişkin problemler çözümlenmiştir. Bu operasyon modunun dizin olarak kullanılması çok daha yüksek akustik çıkış gücü elde edilmesine olanak sağlamaktadır. Darbe genişlik modülasyonu (PWM) sinyali elektriksel giriş olarak kullanılarak daha iyi sinyal iletimi sağlanması hedeflenmiştir.

CMUT'ların tasarım sürecinde büyük işaret modeli kullanılmıştır. Hacimsel iletim yapabilmek için 16×16 (256 eleman) fazlı dizin konfigürasyonu kullanılmıştır. Tasarım prosedürü, Rayleigh uzunluğu ve yığın eleman modeli parametreleri dikkate alınarak oluşturulmuştur. Bu prosedür rezonans frekansları 7.5 MHz ve 18.5 MHz olan iki farklı dizin için uygulanmıştır. Farklı görev döngüleriyle Gauss dağılımlı ton darbesi, sürekli sinusoidal ve PWM sinyalleri kullanılarak harmonik dengeleme ve zaman alanı simülasyonları yapılmıştır.

Doğrulama amacıyla bu simülasyonların sonuçları hüzmleme analizi yapabilen yazılımlara girdi olarak verilmiştir. Simülasyonlara karşılık gelecek şekilde deneysel ölçümler de ultrason ölçüm cihazı kullanılarak elde edilmiştir.

7.5 MHz için tasarlanan CMUT dizinindeki elemanların boyutları 80 μm yarıçap, 15 μm membran kalınlığı, 171 nm efektif açıklık yüksekliği ve 192 μm iki eleman merkezleri arası açıklık olarak belirlenmiştir. Dizin tasarımına göre 45.3 mm Rayleigh uzunluğu ve -17.4 dB yankulak seviyesi elde edilmiştir. Belirlenen bu özelliklere göre CMUT dizini gofret ölçğinde yığın fabrikasyon uyumlu üretim tekniği benimsenerek üretilmiştir. Üretim sürecinde konvansiyonel litografi adımları için kullanılmak üzere sadece iki litografi maskesi kullanılmıştır. Salınım yapan membran anodic gofret yapıştırma tekniği ile üretilmiş, fabrike edilen CMUT dizinleri fiskeli yonga teknolojisi kullanılarak baskılı devre kartlarına yapıştırılmıştır.

MEMS teknikleriyle üretilen ve konvansiyonel makro ölçekle üretilen devre kartlarına entegre edilen bu yeni cihazın ölçümleri ultrason ölçüm cihazı kullanılarak tamamlanmıştır. Simülasyon sonuçlarını doğrulamak adına basınç ölçümleri alınmıştır.

Anahtar Kelimeler: Kapasitif Mikroışlenmiş Ultrasonik Çeviriciler, CMUT, MEMS, Dizin, Doğrusal (DA) Yüklemez Operasyon, Yarı Frekansta Sürülen, Mutual Radyasyon Empedansı, Suda Çalışan, Hacimsel İletim, Büyük İşaret Eşdeğer Devre Modeli.

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Chapter 1

Introduction

Capacitive micromachined ultrasonic transducers (CMUTs) are first introduced as surface micromachined electrostatic ultrasonic air transducers in 1994 [1] [2]. Rapidly after definition of CMUTs, usage of these devices considered in waterborne and similarly biomedical applications [3] [4]. Wide bandwidth nature [5], different operation modes, such as collapsed, [6] [7] uncollapsed and [8] unbiased (or charged) [9] [10], and compatibility of these devices lead them to be more popular with increased research.

CMUTs are devices that consists a substrate and a moving membrane with a gap designated between these two elements. Substrate and the membrane are used as electrodes for electroacoustic transduction. Using this substrate also as a membrane is presented earlier as bilateral CMUT cells [11]. CMUTs are widely used for receivers because of their high signal-to-noise ratio, which is limited by the noise of the integrated electronics. Also transmitting CMUTs are highly researched to compete with the high power transmission with conventional piezoelectric transducers [12]. Even though sufficient power or received signal can be maintained by using single CMUT cells, for beamforming and higher power transmission capabilities, CMUT arrays are widely used [13] [14].

Another attractive feature of CMUTs is the applicability of micromachining techniques on the fabrication of these devices [15]. Number of different fabrication methods are applied and presented for these devices. Two main methods are discussed, which are wafer bonding [16] and sacrificial layer release processes [17]. Within the sacrificial release processes, commercial multi-user compatible processes are also utilized, such as PolyMUMPS [18]. For wafer bonding process, bonding of a dielectric such as Pyrex as the substrate and a conducting membrane for top electrode such as silicon wafer can be used with a dielectric layer between top and bottom electrode. Conventional MEMS

processes can be applied for bottom electrode fabrication, dielectric layer deposition and gap formation. With the use of wafer bonding, batch compatible wafer scale microfabrication is utilized, which is a huge advantage for mass production of these devices. By this way large number of devices can be manufactured on a single wafer for commercial use. Along with the advantages of MEMS processes, also integration of electronics with these devices becomes an attractive issue. For this purpose flip-chip bonding [19] or CMUT-on-CMOS arrays [20] are widely used.

Though, CMUT devices are impressive with its fabrication and operational advantages, design and modelling of these devices is a cumbersome process. Commercial finite element modelling (FEM) tools are widely used for designing and simulating these devices [21] and huge improvements are gathered with the development of computational power [22]. For mechanical characterization and understanding the principles of these devices FEM is seen as a suitable tool [23]. However, using FEM for arrays with large number of CMUT cells is not a feasible option. Thus, several lumped-element models are presented for modelling both receiver (small signal) and transmitter (large signal) structures of these devices for different mode of operations [24] [8] [10]. By considering the mutual radiation impedance, simulations of arrays with large number of elements also become applicable [25]. With the use of equivalent circuit models, conventional lumped-element circuit model simulators can be used, which significantly decreases the computational time. Thus, using a conventional circuit simulator that can solve nonlinear operations creates a simple and practical simulation environment. Another advantage of using lumped-element modelling in CMUTs is that the formation and analysis of spurious resonances, such as Rayleigh-Bloch wave resonances on the surface of the transducer [26]. Similar spurious resonances and non-uniformities is observed and analysed with this method [27], where in FEM it is not possible.

In this work; modelling, simulation, fabrication and experimental verification of transmitting waterborne CMUT array with 256 elements (16×16)

array configuration) by using the unbiased mode of operation is done. Design procedure and measurements were presented for an airborne CMUT cell without a DC bias earlier [9]. Several advantages come along with the unbiased mode of operation. In unbiased mode, the frequency of sinusoidal electrical input signal is half of the resulting acoustical output signal and the plate motion spans the entire gap without collapsing. A large plate swing can be obtained at low excitation voltages using the entire remaining gap. Using the entire gap for plate swing with DC bias is not possible due to the collapsing feature determined by the CMUT biasing chart [28]. Thus, using the entire gap for plate motion or swing gathers a huge advantage for transmitting CMUTs, which results in higher acoustical power output for lower excitation voltages.

In this work, a design procedure of arrays with unbiased operation mode is derived. Designs are validated by means of simulations and measurements on fabricated CMUTs. The problems associated with beamforming are resolved. Use of this operation mode in an array configuration enables larger acoustical power output. A better transmitted signal waveform definition is obtained when pulse width modulation (PWM) is employed.

In the design process of CMUTs, large-signal equivalent circuit model is used. In order to have volumetric transmission, a 16×16 (256 elements) phased array configuration is chosen. Considering the radiation pattern, Rayleigh distance and the parameters of the lumped-element model, a design procedure is presented. This procedure is applied for designing two arrays, with resonance frequencies at 7.5 MHz and at 18.5 MHz.

Harmonic balance simulations are conducted for frequency spectrum of pressure output, impedance analyses and power computations of the array. Also transient analyses are carried out with gaussian enveloped tone burst, transient sinusoidal and PWM signals with different duty cycles. Mainly pressure outputs and particle velocities of the cells are investigated. As an addition for each transmission waveform Rayleigh-Bloch waves are observed and minimum voltage mode (MVM) is investigated where MVM is the minimum voltage that

the membrane of the CMUT cells can maintain swing over the entire gap height. According to these time domain simulations, power and intensity results are also obtained. Finally, outputs of these simulations are fed in beamforming toolboxes such as k-wave in MATLAB for further verification. Radiation pattern and applicability of conventional beamforming techniques on these transducers are discussed. These results are also used for obtaining field patterns for different transmission schemes.

Designed devices are fabricated by using conventional MEMS processes and wafer bonding technique with using Pyrex wafer as the substrate and silicon wafer as the membrane. Gap heights, insulation and electrode layer thicknesses are applied on Pyrex wafer within a batch compatible wafer scale microfabrication process. Self-aligned process is used where all of the features fabricated on the substrate, Pyrex, are manufactured by using a single conventional photo lithography mask. In total, two lithography masks and one shadow mask is used for whole fabrication process. After MEMS processing, CMUT array devices are integrated on a conventional printed circuit board (PCB) with flip-chip bonding and devices are integrated into a probe.

This work is concluded with the measurements obtained by the fabricated CMUT array as an integrated probe and verification of simulations conducted with the use of lumped-element modelling is done by comparing the results and finally parameters of the equivalent circuit used in the design process is slightly corrected according to these results. As a result, a novel CMUT phased array working with unbiased mode of operation, which can handle various waveform transmission schemes with half frequency electrical input drive. Absence of DC bias prevents charging of CMUTs, where the charging phenomenon remains as a disadvantage of CMUT operation.

Chapter 2

Design of Arrays

2.1 Lumped Element Model and Large Signal Equivalent Circuit

CMUTs can be depicted as parallel plate capacitors and explained by analogy to the forces induced between top and bottom electrodes. Distinctly from the parallel plate capacitors, CMUT's membrane compatibly deflects as a clamped membrane structure, which is demonstrated in Figure 2.1.

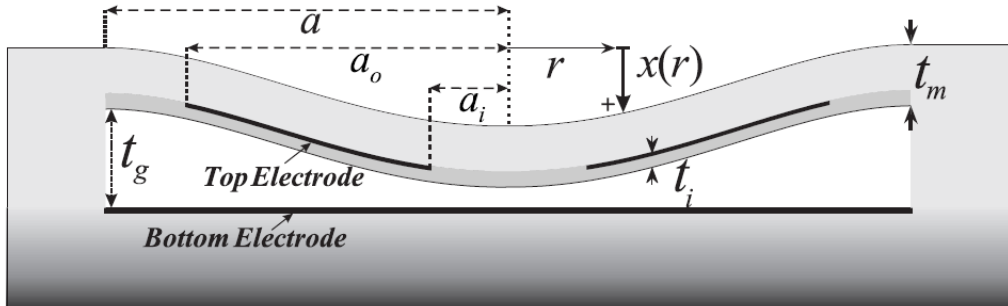


Figure 2.1: Cross-sectional view of circular CMUT and its clamped membrane deflection structure [29].

Membrane displacement (deflection) geometry shown in Figure 2.1 can be analytically explained using plate theory [30], [31] as

$$x(r, t) = x_p(t) \left(1 - \frac{r^2}{a^2} \right) \text{ for } r \leq a \quad (2.1)$$

Since the unbiased mode of operation is an electrically nonlinear operation, another linearity parameter for CMUTs is the elastic nonlinearity. Thus, if the maximum membrane displacement, X_p , is not more than the 20% of the membrane thickness, the membrane displacement operation is accepted to be in the linear region [32].

As explained in Chapter 1, FEM is a very powerful tool for analytical solving and simulation for CMUTs and arrays with small number of elements. As the number of elements in the array is increased, need for computational power rapidly increases. Thus, more convenient simulation method is needed for designing of these transducers.

In 2012, both large and small signal equivalent circuit model is presented [33]. With this lumped element model, conventional circuit analysis software tools can be used for simulating the operation of these devices. In this work, due to the intention of designing transmitting CMUT arrays, for each of the elements in the array, large signal equivalent circuit given in Figure 2.2 is used and parameters for the lumped elements are given in Table 2.1 [33]. Derivations for these parameters are extensively discussed in [29], [33] and [34].

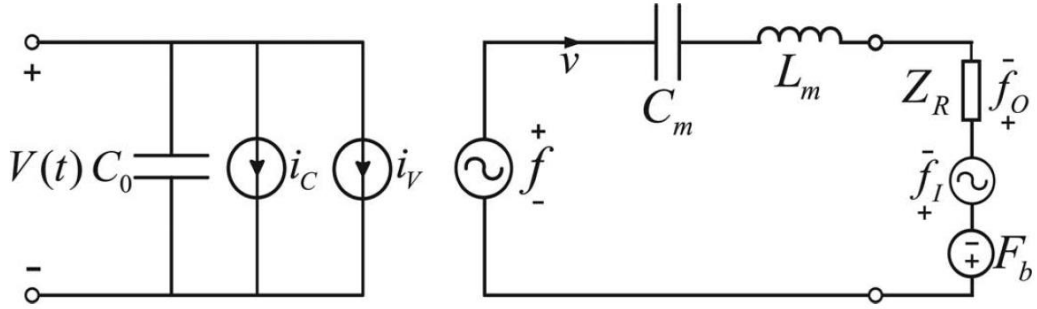


Figure 2.2: Large signal equivalent circuit model for single CMUT cell.

Table 2.1: Parameters of the lumped elements of the large signal equivalent circuit model for single CMUT cell shown in Figure 2.2

Model	RMS $\{f_R, v_R\}$	Average $\{f_A, v_A\}$	Peak $\{f_P, v_P\}$
f	f_R	$\frac{3}{\sqrt{5}} f_R$	$\frac{1}{\sqrt{5}} f_R$
v	v_R	$\frac{\sqrt{5}}{3} v_R$	$\sqrt{5} v_R$
C_M	$C_{Rm} = \frac{9(1-\sigma^2)a^2}{5 \cdot 16\pi Y_0 t_m^3}$	$C_{Am} = \frac{5}{9} C_{Rm}$	$C_{Pm} = 5 C_{Rm}$
L_M	$L_{Rm} = \rho \pi a^2 t_m$	$L_{Am} = \frac{9}{5} L_{Rm}$	$L_{Pm} = \frac{1}{5} L_{Rm}$
Z_R	Z_{RR}	$Z_{AR} = \frac{9}{5} Z_{RR}$	$Z_{PR} = \frac{1}{5} Z_{RR}$
f_i	$\pi a^2 p_{in}$	$\frac{3}{\sqrt{5}} \pi a^2 p_{in}$	$\frac{1}{\sqrt{5}} \pi a^2 p_{in}$
f_o	$\pi a^2 p_o$	$\frac{3}{\sqrt{5}} \pi a^2 p_o$	$\frac{1}{\sqrt{5}} \pi a^2 p_o$
F_b	$\frac{\sqrt{5}}{3} \pi a^2 P_0$	$\pi a^2 P_0$	$\frac{1}{3} \pi a^2 P_0$

One of the most important concepts in designing and operation of acoustical transducer arrays is the mutual radiation impedance. Due to the closely packed structure of the CMUT elements in an array configuration, operation of each CMUT element is affecting all other elements. For this coupled operation, mutual radiation impedance for individual CMUT cells are defined as [24]

$$Z_i = Z_{ii} + \sum_{\substack{j=1 \\ i \neq j}}^N \frac{v_j}{v_i} Z_{ij} \quad (2.2)$$

where N is the number of cells in the array, Z_{ii} is the self-radiation impedance and Z_{ij} is the mutual radiation impedance between the i^{th} and j^{th} elements [35].

Upon the calculation of self and mutual radiation impedances, acoustic force at the radiation interface can be determined by integrating these impedance

values in a matrix format. Thus, for each i^{th} and j^{th} element, calculated impedance can be resulted as a square matrix, which is called the impedance matrix [29]. Matrix multiplication of the impedance matrix with the particle velocity vector results in the acoustic force vector for each cell.

$$\begin{bmatrix} F_1 \\ F_2 \\ \vdots \\ F_N \end{bmatrix} = \begin{bmatrix} Z_{11} & Z_{12} & \cdots & Z_{1N} \\ Z_{21} & Z_{22} & \cdots & Z_{2N} \\ \vdots & \vdots & \ddots & \vdots \\ Z_{N1} & Z_{N2} & \cdots & Z_{NN} \end{bmatrix} \begin{bmatrix} v_1 \\ v_2 \\ \vdots \\ v_N \end{bmatrix} \quad (2.3)$$

Thus, by using (2.3), force, particle velocity and impedance values can be calculated easily for each CMUT cell in the array. Following the calculation for each cell, similar equivalent circuit representation of the CMUT array represents the overall array operation as shown in Figure 2.3 [29].

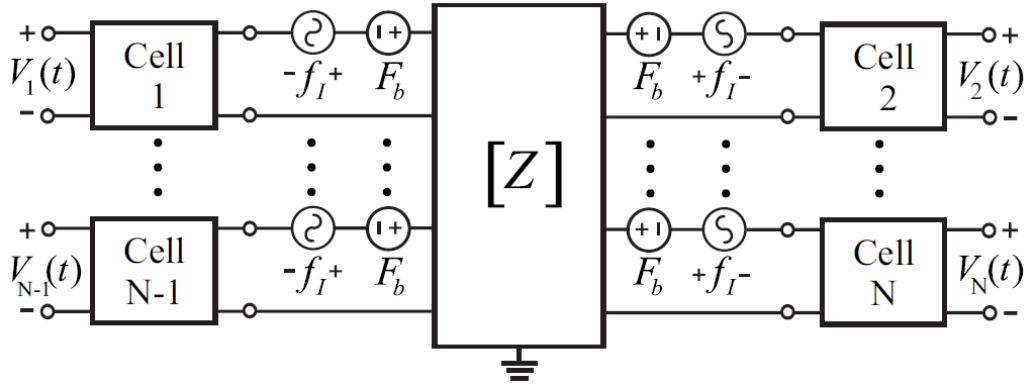


Figure 2.3: Equivalent circuit model representation of the CMUT array with N cells, where the blocks denoted as ‘Cell’ consists of the large signal equivalent circuit shown in Figure 2.2. F_b is the static external force, such as that due to atmospheric pressure. f_I is the dynamic external force, such as that due to an incident acoustic signal [29].

In this work, unbiased mode of operation is applied on phased array configuration. In unbiased operation, biasing of the membrane is accomplished by stress instead of DC voltage. Since force term in (2.4) depends on square of the electrical input voltage, the resulting force term’s frequency becomes twice the AC voltage input.

$$f_R(t) = \sqrt{5} \frac{C_0 V^2(t)}{2t_{ge}} g' \left(\frac{x_p(t)}{t_{ge}} \right) \quad (2.4)$$

2.2 Design Considerations

The design process of CMUTs are consisting several limitations and considerations. Majority of these considerations were depending on the ultrasound measurement system, DiPhAS (Digital Phased Array System, Fraunhofer IBMT, Frankfurt, Germany). This system designed for our research group by Fraunhofer IBMT and it has 256 dedicated channels for reception and transmission of ultrasound signals from 1 MHz to 20 MHz mid-frequency transmit range. Usable output voltage is limited by 150 V_{pp} and transmit pulse is formed as selection of standard gaussian enveloped tone burst with selection of frequency, cycle count and polarity. Also having tri-state transmitter, customized signals can be transmit by using tri-state PWM signals with the digitalization resolution of 2.1 ns.

Firstly, the acoustical operating frequencies were determined. Selection of these frequencies made according to the transmittable frequencies of DiPhAS and the ultrasonic probes (piezo) that our research group has already owning. Thus, 7.5 MHz for mid frequency range and 18.5 MHz for high frequency range chose. Transmitted signal frequency for DiPhAS determined by the following equation (480 MHz is the clock frequency of the FPGA in DiPhAS).

$$f = \frac{480 \text{ MHz}}{(2 \times (\text{predefinedBurstHalfwaveClockCount} + 1))} \quad (2.5)$$

Since predefined burst halfwave clock count value has to be an integer value, selectable frequencies are limited. For the selected frequencies of 7.5 MHz and 18.5 MHz, predefined burst halfwave clock counts are 31 and 12 respectively.

Also by considering the input/output channels of DiPhAS, transmitter is designed to have 256 elements. In order to have symmetry in both elevation and

azimuth planes, placement of elements into an array concluded to be 16 by 16 elements (in a square manner).

2.3 Single Cell and Array Parameters

After deciding on the operating frequencies, physical dimensions are determined by considering again the limitations of DiPhAS, fabrication capabilities and directivity of the array. Starting point for determining the cell radius was choosing the the value of wavenumber times the radius, ka . One of the major effects on directivity of an element is based on this value.

In order to eliminate other modes of operation on the determined wavelength, ka value has to be less than π [36]. On the other hand, sidelobes of the directivity of the array depends on the pitch, d , between the successive array elements. In order to avoid any sidelobes in the radiation pattern of the array, relation between d and wavelength, λ , is;

$$d < \frac{N-1}{N} \lambda = \frac{15}{16} (200 \times 10^{-6}) = 187.5 \mu m$$

where N is the number of elements in one row of the array [37]. Thus, in this case the pitch should be less than 187.5 μm . However, finding the optimum ka and kd value depends on the Rayleigh distance, R_0 . This distance determines the maximum beamformable region. Since these transducers are aimed to be used in biomedical applications, beamforming is a fundamental issue in ultrasonic image forming. Thus, for an ultrasonic transmitter having maximum Rayleigh distance while not having sidelobes is a crucial property for clear transmission of acoustical signal. This property becomes the starting point of this design.

$$R_0 = \frac{S}{\lambda} \quad (2.6)$$

As indicated in [37] Rayleigh distance is based on the area of the array and the wavelength of the operating frequency. On the other hand, for clamped plate structures, the radiation pattern (amplitude directivity function) D_p is given as,

$$D_p(\theta, ka) = 48 \frac{J_3(ka \sin(\theta))}{(ka \sin(\theta))^3} \quad (2.7)$$

where J_3 is the third order Bessel function [38]. After determining the desired radiation pattern of single element of CMUT (which is an omni-directional pattern in this case) radiation pattern of the 16×16 array is calculated by using (2.8), independent of the cell radius.

$$D_a(\theta) = \frac{1}{n} \frac{\sin\left(\frac{n\pi d}{\lambda} \sin(\theta)\right)}{\sin\left(\frac{\pi d}{\lambda} \sin(\theta)\right)} \quad (2.8)$$

After obtaining the radiation pattern of the array configuration, overall radiation pattern of the array including the configuration, pitch and cell radius is obtained by using the array theorem [37].

$$D(\theta) = D_a(\theta) \times D_p(\theta, ka) \quad (2.9)$$

By using these three equations, maximum Rayleigh distance with minimum sidelobe level (SLL) for possible radius and pitch values obtained, with a written MATLAB script. After filtering these optimized radius and pitch values, fabrication limitations are also considered. Since the array constructed as 16×16 elements, wiring of each of these elements is a critical issue. In order to have an efficient use of area, the number of wires that needs to be placed between two consecutive outermost elements of the array is 196, while having 60 opening areas for the inner elements to fan out. Thus, using 16 openings for 4 wires and 44 opening for 3 wires to fan out efficient wiring can be obtained. However, the regions where four wires passing through these openings can be fragile in fabrication processes. By considering the fabrication limitations in our facilities, minimum width of wire and spacing between wires are set to be 3 μm . Therefore, 27 μm becomes the minimum spacing between two consecutive elements. After putting this last consideration to the MATLAB script for finding the optimum radius and pitch values, calculations give $a = 78.61 \mu\text{m}$, $d = 190.24 \mu\text{m}$ with R_0 of 45.3 mm and -26.38 dB SLL. However, by considering the

accuracy of the fabrication, radius and pitch values are slightly rounded and turned into $a = 80 \mu\text{m}$ and $d = 192 \mu\text{m}$, which gives $R_0 = 46.2 \text{ mm}$ and -17.4 dB SLL . (Calculations and results are for 7.5 MHz)

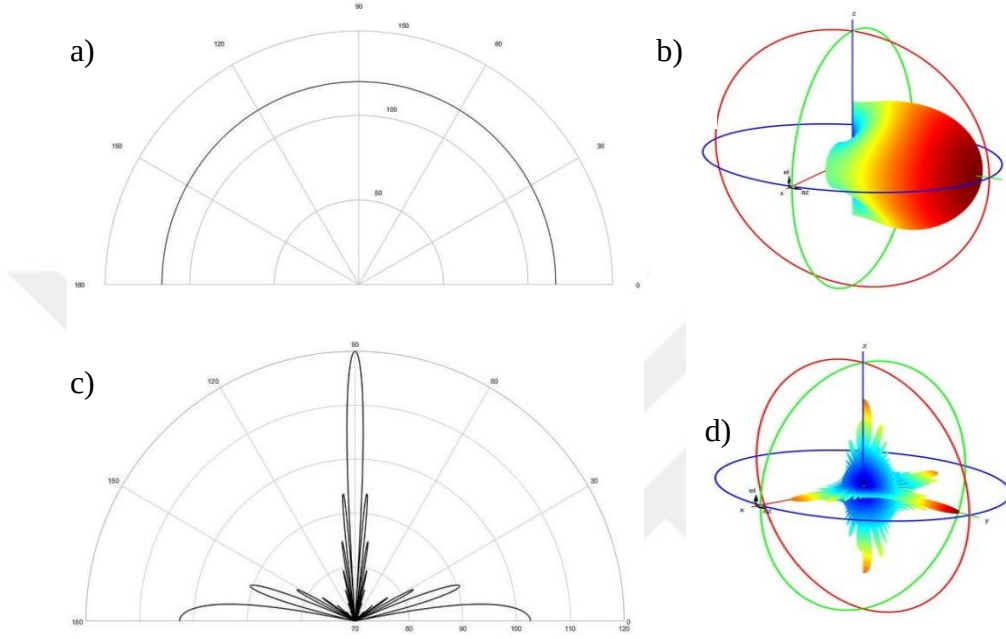


Figure 2.4: Radiation pattern results of transmitter design for 7.5 MHz operation frequency. All figures are given as $\text{dB re. } 1 \mu\text{Pa}$. a) Radiation pattern of a single cell with $a = 80 \mu\text{m}$, $\varphi = 0$ b) 3-D radiation pattern of a single cell for both elevation and azimuth plane, c) radiation pattern of 16×16 array with $a = 80 \mu\text{m}$ and $d = 192 \mu\text{m}$, $\varphi = 0$ d) 3-D radiation pattern of the array.

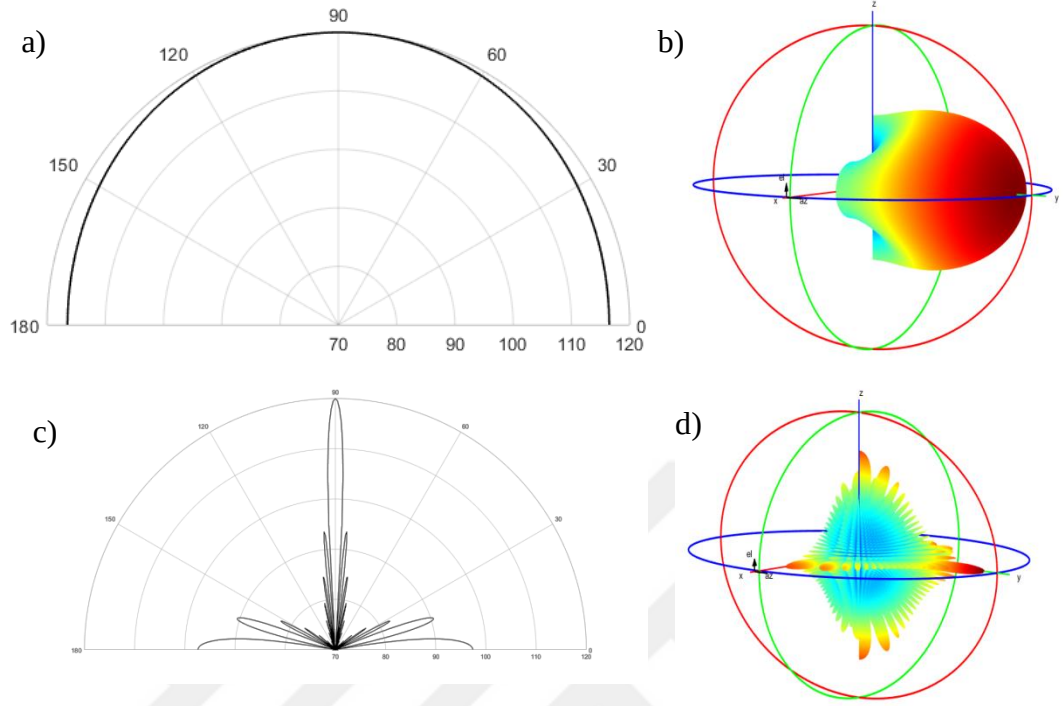


Figure 2.5: Radiation pattern results of transmitter design for 18.5 MHz operation frequency. All figures are given as dB re. 1 μ Pa. a) Radiation pattern of a single cell with $a = 32.2 \mu\text{m}$, $\varphi = 0$ b) 3-D radiation pattern of a single cell for both elevation and azimuth plane, c) radiation pattern of 16x16 array with $a = 32.2 \mu\text{m}$ and $d = 77.8 \mu\text{m}$, $\varphi = 0$ d) 3-D radiation pattern of the array.

After determining the radius of the elements, the plate thickness, t_m , can be obtained by using the resonance equation [33],

$$\omega_m = \frac{1}{\sqrt{L_{Am}C_{Am}}} = \frac{t_m}{a^2} \sqrt{\frac{80}{9} \frac{Y_0}{\rho_m(1 - \sigma^2)}} \quad (2.10)$$

where density, ρ , Poisson ratio, σ , and the Young's modulus, Y_0 are taken for silicon as given in Table 2.2.

Table 2.2: Membrane (Silicon) and insulator (Alumina) parameters that is taken for calculation and simulation in this work.

Membrane and Insulator Parameters		
Y_0	Young's Modulus	149 GPa
σ	Poisson ratio	0.17
ρ	Density	2370 kg/m ³
ϵ	Dielectric constant of Al ₂ O ₃	9

The dynamic force acting on the membrane is the sum of the forces across the compliance and the mass [33]. Hence the compliance (C_{Am}) and the effective inductive loading (L_{Am}) are in series and yields a resonance frequency. Since this resonance frequency is chosen beforehand (7.5 MHz and 18.5 MHz), the only unknown variable becomes t_m . Thus, the equation yields, $t_m = 12.572 \mu\text{m}$. However, by considering the availability of SOI wafers in the repository of our research group, t_m selected to be $15 \mu\text{m}$ for fabrication of the CMUT arrays, which does not dramatically affect both resonance frequency and the output power.

At this point, all the variables that have effect on resonance frequency are calculated and the only design parameter left is the gap height, t_g . Before approaching to determine the gap height several values should be chose. Since the maximum output voltage of DiPhAS is $150 V_{pp}$ there is a limiting value on the input voltage of this transmitter. Also this limiting value helps us to determine the thickness of the insulating layer which will be aluminum oxide in this work. In previous works within our research group, atomic layer deposited (ALD) aluminum oxide's dielectric breakdown voltage is measured as 620 kV/mm. With adding safety regions, dielectric breakdown voltage is set to be 195 V, therefore insulator thickness; t_i is set to 300 nm.

On the other hand, the maximum swing of the plate of the CMUT inside the gap should be maintained. Thus, by determining the collapse voltage at vacuum, V_r , the t_{ge} can be found by using [33],

$$V_r = 8 \frac{t_m}{a^2} t_{ge}^{3/2} t_m^{1/2} \sqrt{\frac{Y_0}{27\epsilon_0(1-\sigma^2)}} \quad (2.11)$$

Considering a safety region, V_r is taken as 100 V. After replacing V_r with this value, effective gap height, t_{ge} calculated as 171.2 nm and gap height, t_g as 137.87 nm for the membrane thickness of 12.572 μm .

$$t_{ge} = t_g + t_i/\epsilon \quad (2.12)$$

According to all these calculated parameters, F_{pb}/F_{pg} , can also calculated. F_{pb}/F_{pg} is a measure of the ambient pressure relative to the stiffness of the membrane. At a fixed ambient pressure, such as atmospheric pressure, this value is low if the membrane is stiff, while it is close to unity when the membrane is compliant [39]. Also by having a stiffer membrane and thereby less static depression, more swing in gap can be achieved with given electrical energy. By using the equation below [33], F_{pb}/F_{pg} is calculated as 0.0149. Since this value is relatively low, it means that the static depression is low and leaves more room for dynamic movement of the plate with the expense of lower bandwidth.

$$\frac{F_{pb}}{F_{pg}} = \left(\frac{t_m}{t_{ge}}\right) \left(\frac{a}{t_m}\right)^4 \frac{3}{16} \frac{P_0(1-\sigma^2)}{Y_0} \quad (2.13)$$

After calculating F_{pb}/F_{pg} , an accurate approximation for the collapse voltage found as 98.48 V by using [33],

$$\begin{aligned} \frac{V_c}{V_r} \approx & 0.9961 - 1.0468 \frac{F_{pb}}{F_{pg}} + 0.06972 \left(\frac{F_{pb}}{F_{pg}} - 0.25 \right)^2 \\ & + 0.01148 \left(\frac{F_{pb}}{F_{pg}} \right)^6 \end{aligned} \quad (2.14)$$

According to [33], (2.11) and (2.14) is given for DC biased operation. Thus, in this mode of operation, calculated values are not directly applicable. Firstly, in unbiased operation, collapsing of membrane is not occurring; hence, collapse voltage concept is not applicable. Instead, the minimum voltage level, where the maximum swing of the membrane is maintained, can be determined, which is also presented as *minimum voltage mode (MVM)* in [9]. Also it is known that AC voltage peak value can be used as a DC value by dividing AC voltage peak value to square root of two. Thus, with a small modification to the collapse voltage calculation in (2.14), very good approximation of *MVM* can be found, where this calculation is verified by the simulations done in Section 3.5 Gaussian Enveloped Tone Burst Signal.

$$MVM \approx V_c \times \sqrt{2} \quad (2.15)$$

Finally, after deciding on these parameters the lumped element modelling is used for fine-tuning and output power maximization. Since non-linear operation is highly effective in this mode of operation, harmonic balance is critical for further verification.

In this work, as explained earlier, fabrication limitations are very significant during the course of design procedure and simulations. Thus, by selecting t_m as 15 μm , t_g , decrease to 85.12 nm, which is infeasible considering our limitation capabilities. Thus, for the simulations, 138 nm gap height is chosen by considering feasible and possible fabrication outcomes and precision of gap height formation.

2.4 Design Procedure of Waterborne CMUT Arrays

A CMUT cell and array for unbiased transmission operation can be designed using (2.6), (2.9), (2.10), (2.11) **Error! Reference source not found.** and (2.15). According to the area of application, by determining the suitable

Rayleigh distance and radiation pattern, suitable CMUT cell parameters can be calculated. Summarized design approach is as follows:

- 1) Find the optimum radius of the cell, a , and the pitch of the elements of the CMUT array, d , according to the desired Rayleigh distance and radiation pattern.
- 2) From the specified operation frequency, find the plate thickness, t_m using (2.10).
- 3) Set an allowable value of collapse voltage at vacuum, V_r and find effective gap height, t_{ge} using (2.11).
- 4) Find F_{pb}/F_{pg} and calculate MVM .
- 5) Use lumped-element modelling for fine-tuning and calculate the necessary steps recursively.

For specific desired MVM , V_r can be used in (2.15) **Error! Reference source not found.** instead of V_c , for the first iteration on finding the effective gap height, which will give an accurate estimation for MVM if F_{pb}/F_{pg} is close to zero.

This approach is applied for our other selected frequency, 18.5 MHz, without considering any fabrication limitations. After applying this design procedure, design parameters for both 7.5 MHz and 18.5 MHz are calculated as in the following table.

Table 2.3: Designed CMUT parameters for two different operation frequencies.

		CMUT – I	CMUT – II
f	Resonance frequency (MHz)	7.5	18.5
a	Plate radius (μm)	80	32.2
d	Element pitch (μm)	192	77.8
SLL	Sidelobe level (dB)	-17.4	-22.6
R_0	Rayleigh Distance (mm)	46.2	18.5
t_m	Plate thickness (μm)	15	5
t_{ge}	Effective gap height (nm)	171.2	101.8
t_i	Insulator thickness (nm)	300	300
t_g	Gap height (nm)	137.8	68.5
F_{pb}/F_{pg}	Normalized exerted pressure	0.01 @SAP	0.01 @SAP
MVM	Minimum Voltage Mode (V)	182.8	100.0

Chapter 3

Simulation Results

3.1 Simulation Specifications

As indicated in Section 2.2, simulation specifications are also considered accordingly to the DiPhAS' clock rate and other properties. Since, the clock rate of the FPGA that is used for transmission in DiPhAS is 480 MHz, same clock rate is used for the simulations (especially for the transient analysis). Thus, the time domain resolution is set to be 2.083 ns.

In all simulations electrical input frequency is given as half of the desired acoustic output frequency. Furthermore, most of the simulations are done for two different voltage levels of 5 and 75 volt. Majority of the simulations done at 5 volt is given in Appendix B.1 Extra Simulation Graphics.

Also, in Advanced Design System (ADS) (Keysight Technologies, Santa Rosa, CA, USA) and k-wave simulations, fabrication limitations are considered. The grid sizes in k-wave are set to 32 μm for 7.5 MHz simulations. The drawback of having smaller grid size is the increasing computational power. As the grid size gets smaller, the computational area for simulation cannot be infinitely large and also for having computational grid size more than 1024 grids results in very long simulation run times. However, having larger grid sizes result in false results. Similar specifications are chosen for 18.5 MHz design and explained in Chapter 3.7 Radiation Pattern Simulations.

Also for the ADS, gap height, t_g , is set to 138 nm. However, in fabrication it is already known that having such a precise resolution in depth is not feasible but for compactness and completeness gap height is taken as the calculated value in Chapter 2.

Another consideration in simulations was the presence of Rayleigh-Bloch waves in this CMUT array. Since the size of the array is much larger than the operating wavelength, Rayleigh-Bloch waves come to exist as explained in [26]. Presence and analysis of these spurious waves are also discussed.

Lastly, through this chapter, since presenting the results for each 256 element is not possible, some important portions of results are presented. Elements where major changes can be seen are shown, such as the corner (1st element), side (128th element) and middle (120th element) elements are shown. The differences are mostly caused by the mutual radiation impedance and effect of the rigid baffle around the elements.

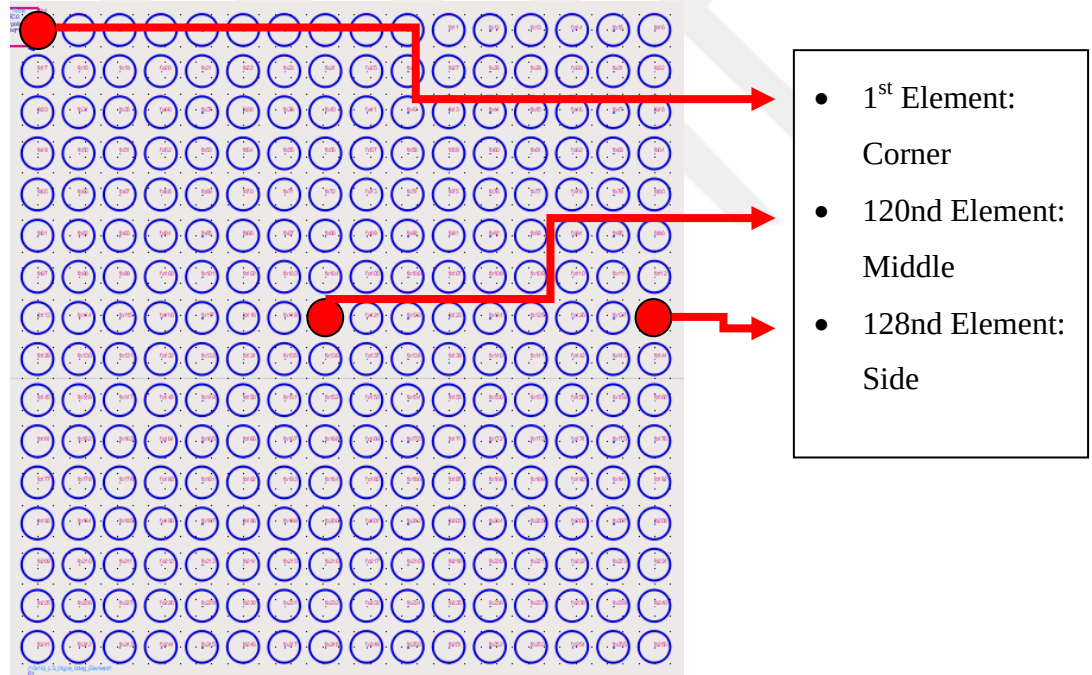


Figure 3.1: Orientation and placement of the elements that will be analysed through this work.

In Figure 3.2 the whole simulation flow is explained. In this work, ADS and MATLAB is used coherently and recursively. All of the output signals are obtained by ADS according to the designed transducer specifications and these output signals are used for beamforming and radiation pattern analysis in

MATLAB. Also the delay calculations are made in MATLAB and fed into ADS for beamforming simulations. Further details are explained in corresponding sections.

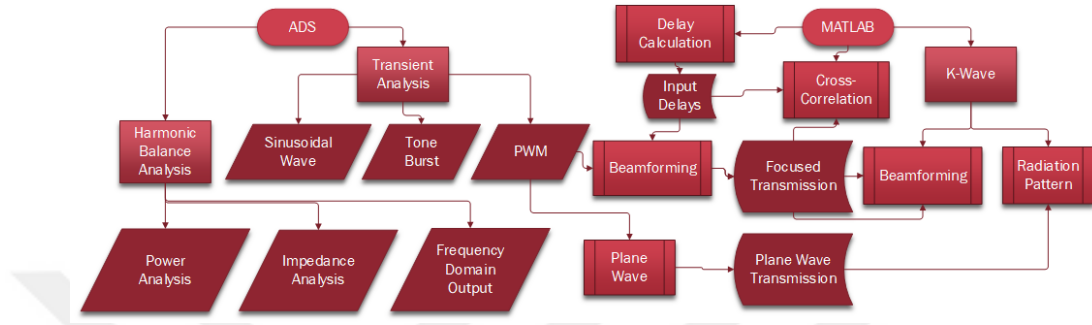


Figure 3.2: Simulation flow diagram

3.2 Harmonic Balance Analysis

The highly nonlinear nature of this operation mode needs to be inspected through a nonlinear analysis tool. Since the lumped element model is constructed in a conventional circuit simulator like ADS, harmonic balance analysis can be done for nonlinear operations.

For 7.5 MHz transducer, frequency is swept from 1 MHz to 15 MHz with 50 kHz step sizes. Second harmonic of the resulting harmonic balance output is presented in order to analyse the frequency domain output of this transducer. Since the phase difference of force outputs between the elements in the array is negligible, magnitude of the force is used to calculate the pressure outputs of the transducer. Similarly, frequency axis is the second harmonic of the sweep frequency. Resulting frequency domain outputs are shown for AC input voltage of 75 volts and zero DC voltage. According to the results, 232.8 dB re 1 μ Pa pressure is obtained at the operation frequency, 7.5 MHz.

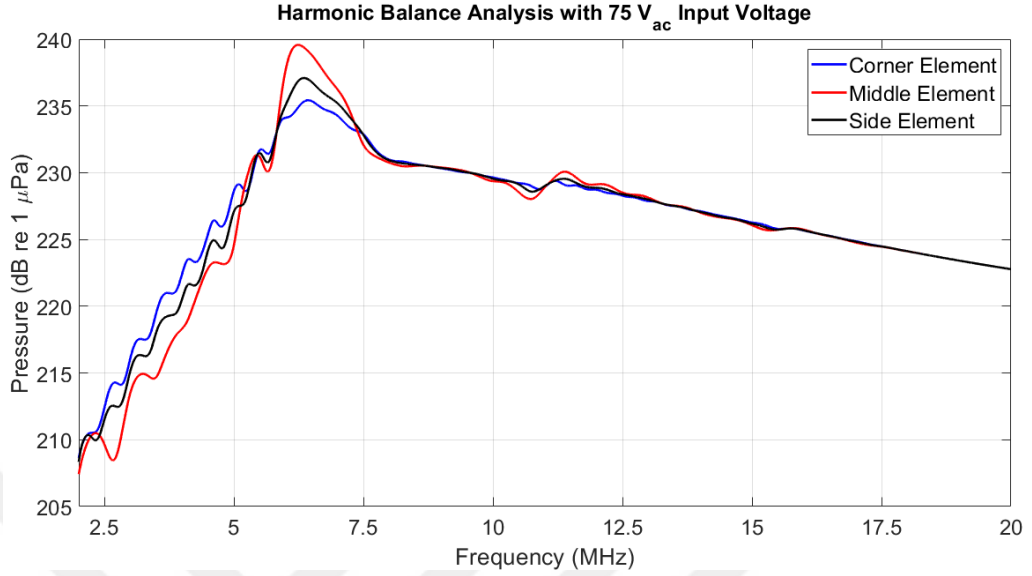


Figure 3.3: Second harmonic results of harmonic balance analysis driven with 75 volts AC voltage and zero DC bias for 7.5 MHz transducer.

Apart from the operation frequency, peak at 6.36 MHz with 240.6 dB re 1 μ Pa is observed. However, due to the narrow bandwidth structure, this peak is not considered as the resonance frequency in this work. Instead this frequency is called as the peak frequency. Due to the undesirable properties in transient response at this frequency, it is decided to select the operation frequency of 7.5 MHz at the right side of this peak.

Using lumped-element modelling provides the ability of simulating arrays with large number of elements. Unlike FEM, formation of spurious resonances and non-uniformities can be observed and resulted with this method. Given that results obtained by harmonic balance analysis shows the presence of resonances at lower frequencies than the operation or peak frequency of the designed transducer where the Rayleigh-Bloch waves are excited on the surface of the transducer. Presence of Rayleigh-Bloch waves indicate the nonuniformity among cell velocities of the array elements mainly due to the unequal radiation resistance impedance seen by the cells, which can be seen in Figure 3.6. Although these waves do not result in a significant degradation on the point spread function but the oscillations that can be observed in time domain analysis, limits the dynamic range and extends the duration of the impulse

response or tone burst [26] [27]. Unlike biased operation, where the spurious resonances caused by the Rayleigh-Bloch waves occur at the lower side of the resonance frequency, in unbiased mode of operation there is also spurious peaks on the right hand side of the operation frequency, which must be investigated further.

For each individual CMUT cell in 16×16 phased array transducer, pressure outputs are obtained and shown as a heat map. This map is shown in both the operation frequency and for the peak frequency. It is observed that the pressure difference between individual cells at the operation frequency is less than the pressure difference at peak frequency of 6.36 MHz. At 7.5 MHz the pressure difference is approximately 0.7 dB, while at 6.36 MHz, the pressure difference becomes more than 5 dB between individual CMUT elements in the transducer array.

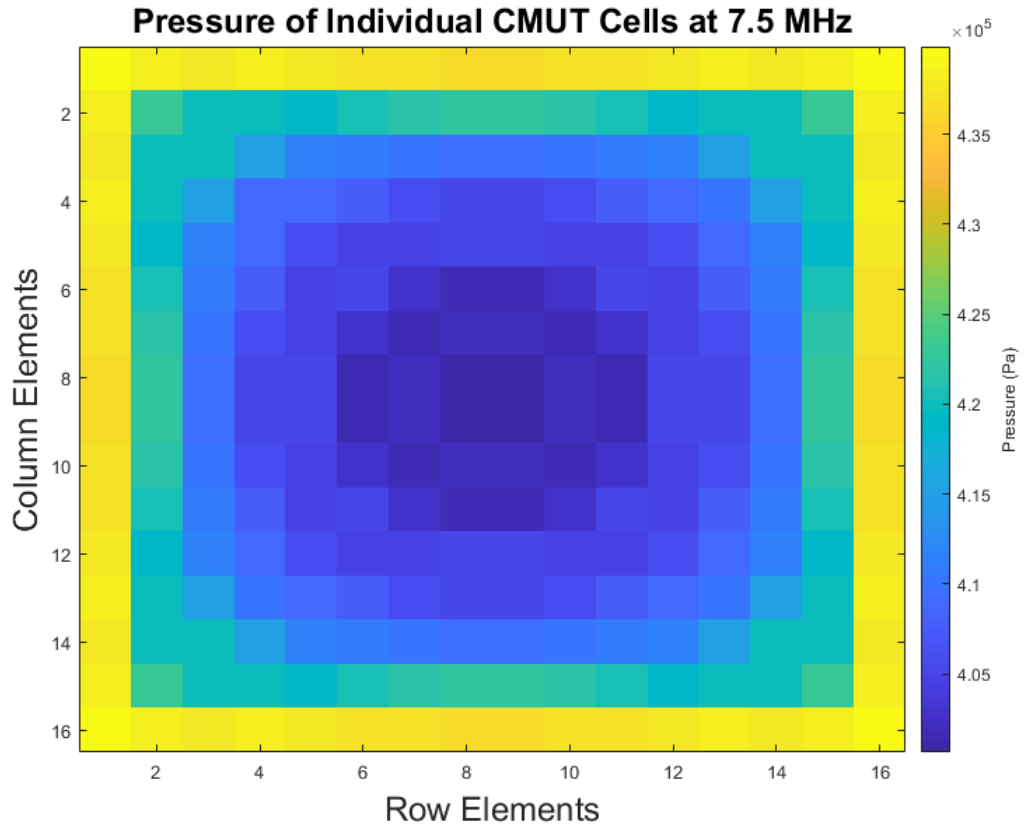


Figure 3.4: Heat map of pressure output of individual CMUT cells of the 16×16 phased array at the operation frequency, 7.5 MHz.

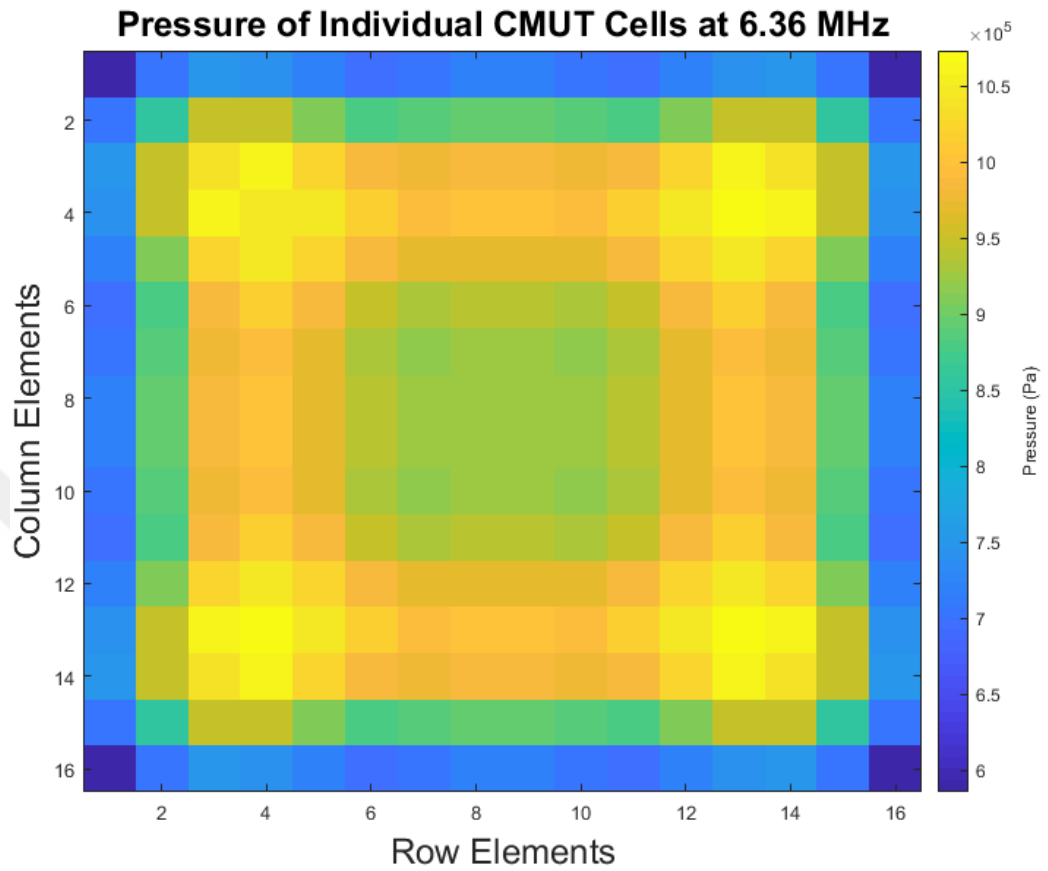


Figure 3.5: Heat map of pressure output of individual CMUT cells of the 16×16 phased array at the peak frequency, 6.36 MHz.

After obtaining pressure results from harmonic balance simulations, another important factor in the operation of CMUTs, particle velocity is observed. The same peak frequency is observed in particle velocity frequency domain analysis and also higher difference of particle velocity between elements is observed compared to pressure results. Heat map for particle velocity is also shown in order to compare the difference of particle velocity between each individual element. It is observed that the power difference between CMUT cells is mostly caused by the difference of particle velocity between the elements.

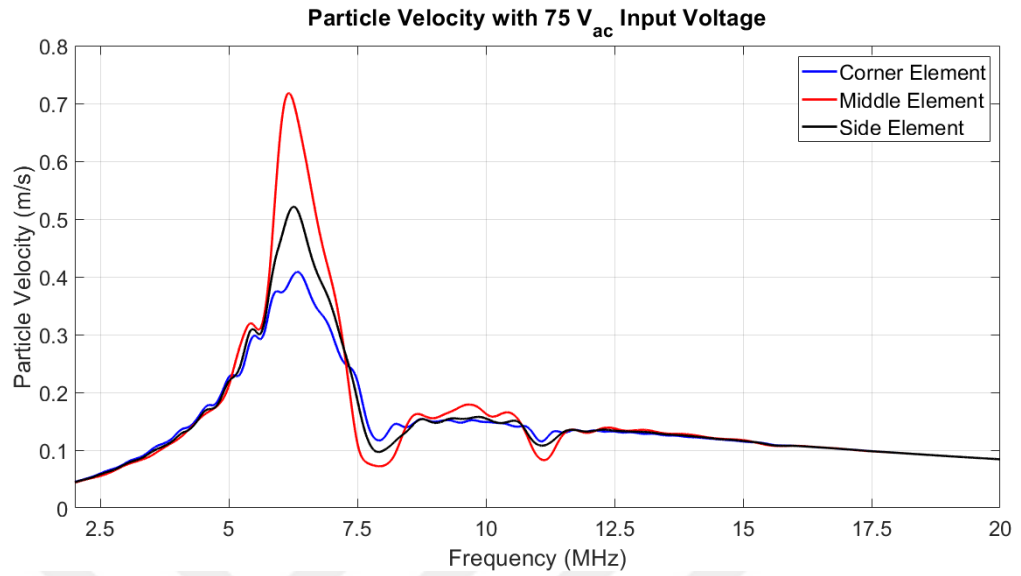


Figure 3.6: Particle velocity frequency domain analysis with 75 V_{ac} input voltage.

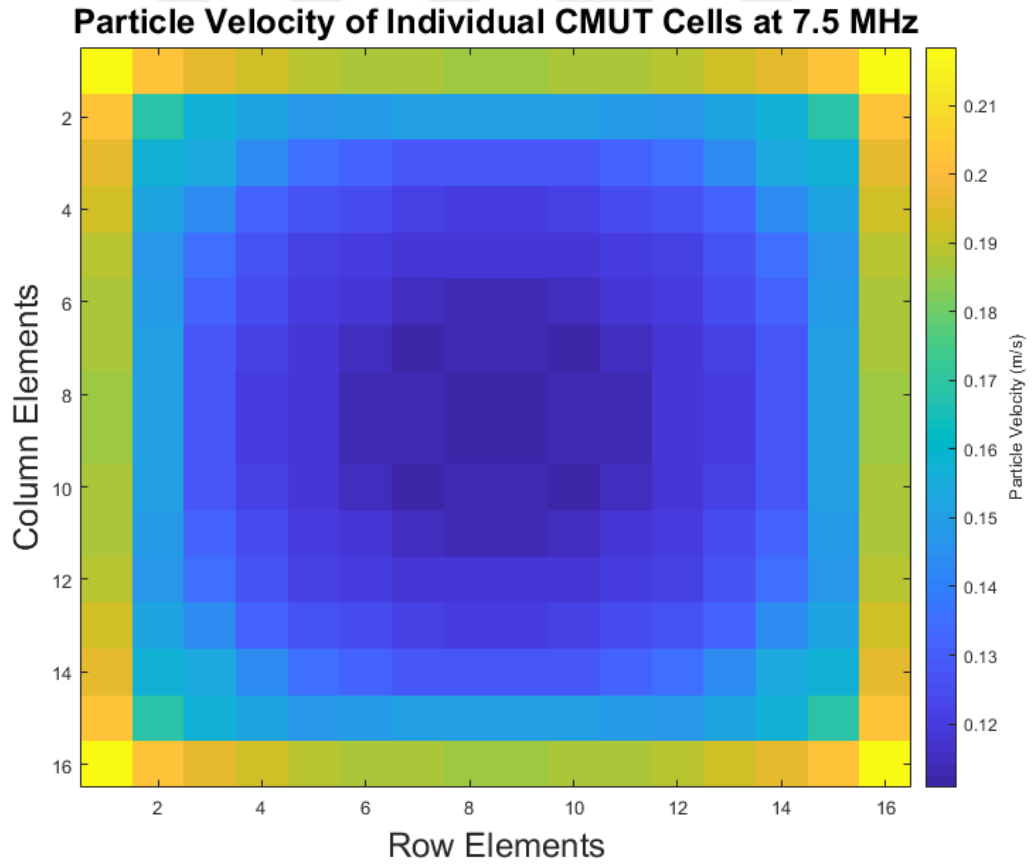


Figure 3.7: Heat map of particle velocity output of individual CMUT cells of the 16×16 phased array at the operation frequency, 7.5 MHz.

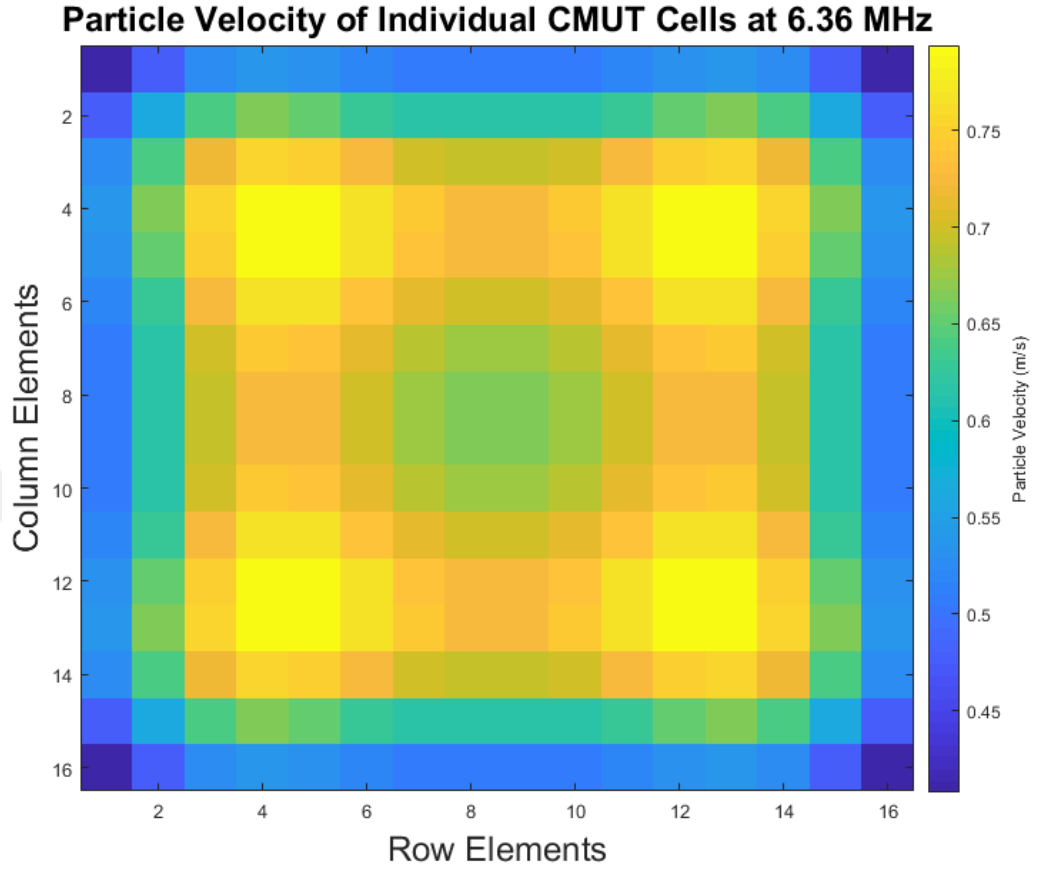


Figure 3.8: Heat map of particle velocity output of individual CMUT cells of the 16×16 phased array at the peak frequency, 6.36 MHz.

After observing outputs of harmonic balance analysis for unbiased mode of operation, a comparison between biased operation is made. For a fair comparison, average normalized membrane deflection caused by the AC voltage input in unbiased mode of operation with 75 V_{AC} is found to be 0.049 in Section 3.4 Sinusoidal Wave, since the static depression in unbiased mode of operation can only be done with ambient pressure and the biasing is done with stress. Thus, the same amount of deflection had to be maintained with DC bias and it is found to be 52.5 V_{DC}. For the AC input voltage, it is aimed to have the same power output with unbiased operation and biased operation, hence AC voltage set accordingly and found to be 28.8 V_{AC}. According to these specifications harmonic balance analysis are repeated with biased mode of operation.

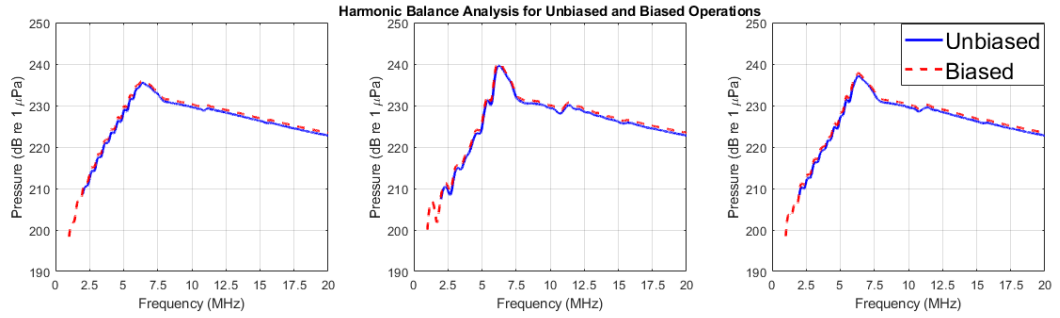


Figure 3.9: Comparison between unbiased and biased mode of operation for corner (a), middle (b) and side (c) elements of the array.

According to the obtained results, the level of force is approximately the same as expected and peak frequency and the Rayleigh-Bloch wave resonances are still remaining in both operation modes. However, by driving the transducer with %55 of the DC voltage as AC voltage, harmonic distortion is inevitable and undesired. Thus, the even harmonics of the electrical input's fundamental frequency in unbiased mode, which is 3.75 MHz, are compared with all the harmonics of the biased mode's input frequency, which is 7.5 MHz. According to obtained force values, total harmonic distortion (THD) is calculated in Table 3.1 and average of 12 dB difference between operation modes is obtained.

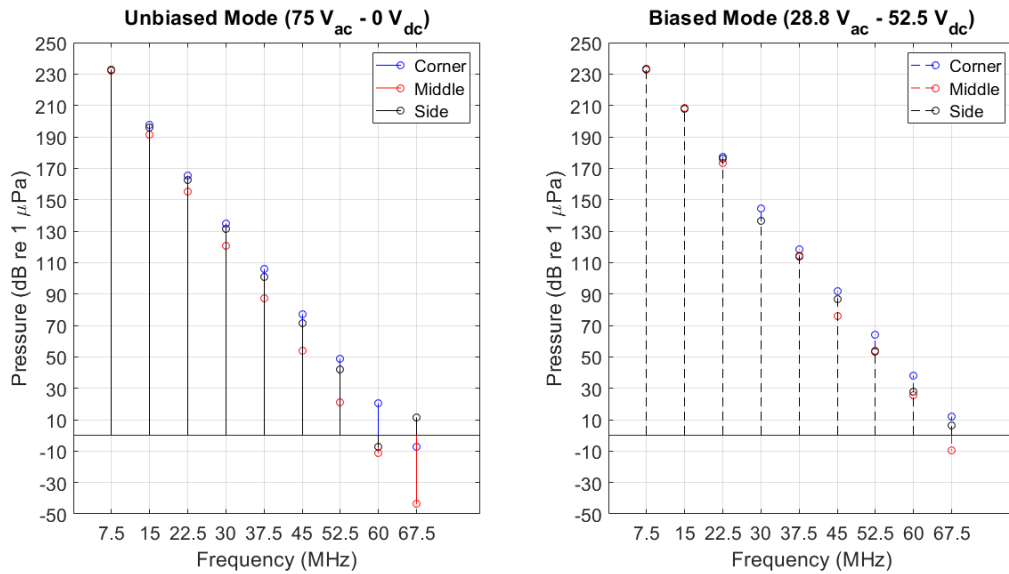


Figure 3.10: Comparison of even harmonics of unbiased mode and all harmonics of the biased mode of operation for critical array elements.

Table 3.1: Total harmonic distortion comparison for different CMUT elements in the array for unbiased and biased mode of operation.

	Unbiased Mode (dB)	Biased Mode (dB)
Corner Element	-35.42	-25.65
Middle Element	-40.49	-24.54
Side Element	-36.87	-25.81

3.3 Impedance Simulations

After completing harmonic balance analysis, same simulation results are used to measure the admittance of each channel for given AC voltage. Conductance and susceptance of the CMUT elements are calculated according to the (3.1) and (3.2) respectively.

$$G = \text{real} \left(\frac{I_{\text{input}}}{V_{\text{input}}} \right) \quad (3.1)$$

$$B = \text{imag} \left(\frac{I_{\text{input}}}{V_{\text{input}}} \right) \quad (3.2)$$

According to these calculations conductance and susceptance values are represented on the same graph accordingly for 75 V_{ac} input.

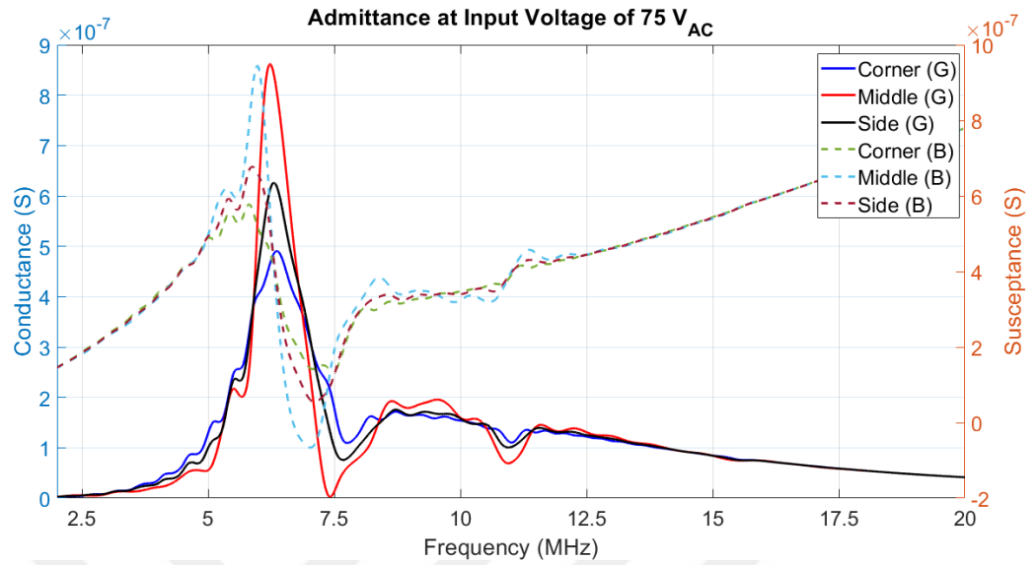


Figure 3.11: Admittance at 75 V_{ac} input voltage. Susceptance values are shown in dashed lines.

Due to the nonlinear nature of this operation mode and driving without DC voltage, admittance values are changing with AC input voltage levels. Thus, admittance calculations and thereby harmonic balance analysis are done with different input voltage levels in order to observe the change in admittance with input voltage.

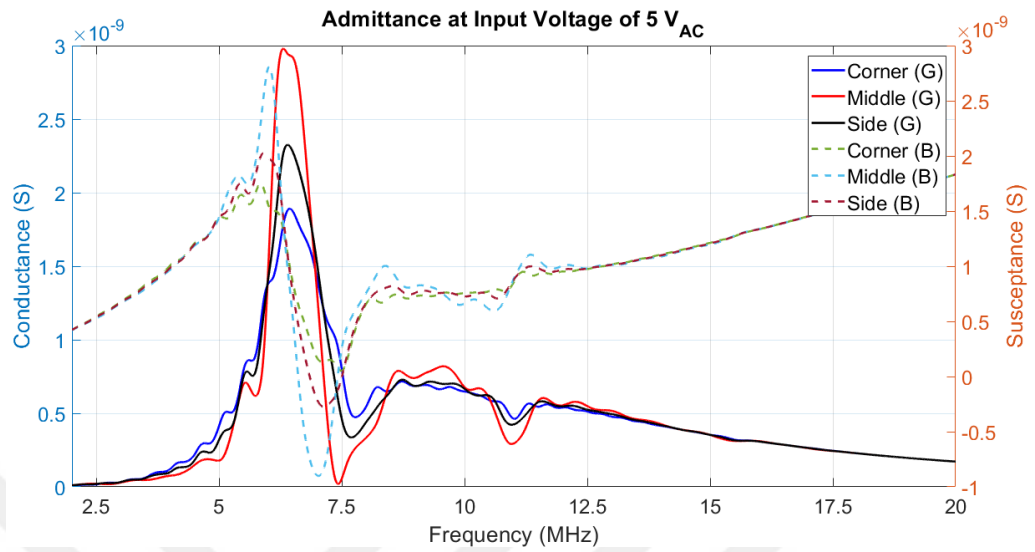


Figure 3.12: Admittance at 5 V_{ac} input voltage. Susceptance values are shown in dashed lines.

By repeating these analyses at 15, 35, and 55 V_{ac}, admittance plots are obtained and shown in Appendix B.1 Extra Simulation Graphics individually. After obtaining admittance graphs at different input voltage levels, conductance and susceptance values at 7.5 MHz are stored and derivation of these values with increasing voltages are shown below.

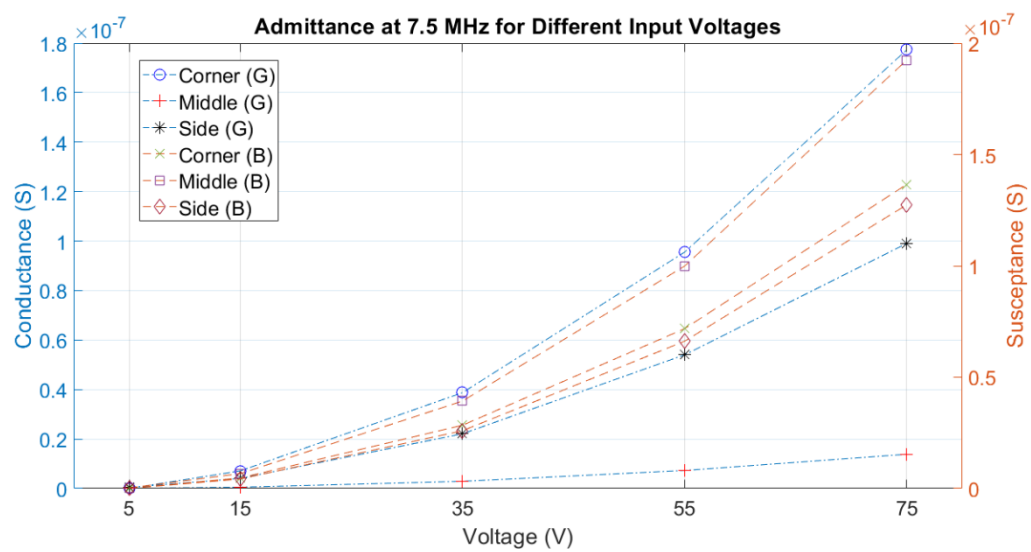


Figure 3.13: Admittance values at 7.5 MHz for different AC input voltage levels.

In order to find susceptance, (3.2), may not be sufficient. By considering the lumped element model for CMUTs [33], on the electrical side of the large signal equivalent model, the current passing through C_0 and the current source i_c shown in Figure 2.2 is dominant over the current source, i_v . Thus, in order to reach i_v , dominant current values have to be subtracted, where the most dominant current given in (3.3) is subtracted [33].

$$j\omega C_0 = j\omega \frac{\pi a^2 \epsilon_0}{t_{ge}} \quad (3.3)$$

3.4 Sinusoidal Wave

Transient analysis are done with the same specifications for 4μs total transmission length, which is the same maximum transmit phase length in DiPhAS. Time domain step sizes are taken as explained in Chapter 3.1 Simulation Specifications. For these analysis two different voltages of 5 and 75 volts is used in order to investigate the difference between minimum and maximum output voltage of DiPhAS. For these specifications output pressures and also their normalized membrane displacement is shown. Output pressure resulted by all elements on the surface of the transducer is also shown.

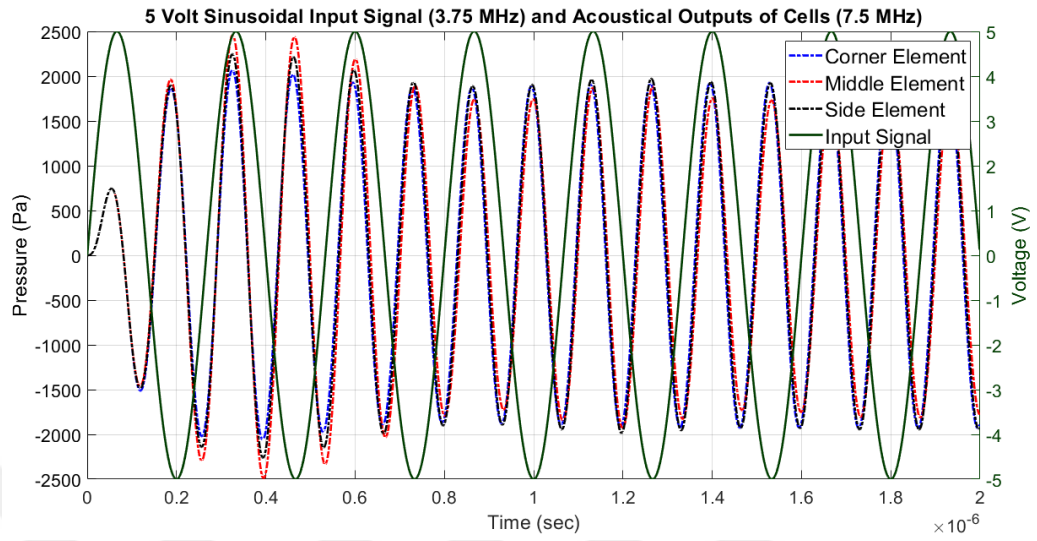


Figure 3.14: Transient sinusoidal transient analysis with 5 volt input voltage at 3.75 MHz frequency is obtained. Acoustical output pressures resulted at 7.5 MHz.

According to the simulations, at steady state 1.933 kPa peak pressure is obtained from single CMUT elements.

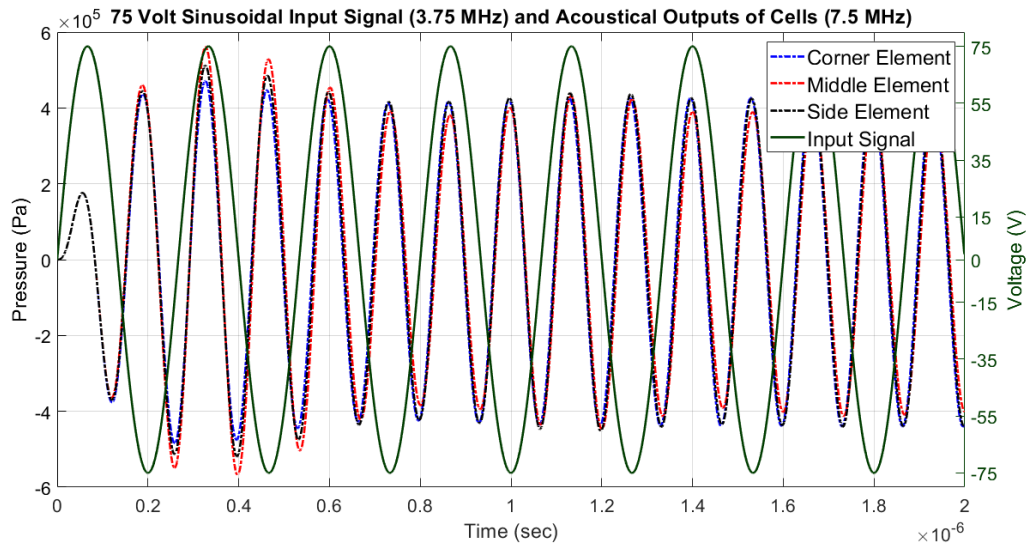


Figure 3.15: Transient sinusoidal transient analysis with 75 volt input voltage at 3.75 MHz frequency is obtained. Acoustical output pressures resulted at 7.5 MHz.

According to the simulations, at steady state 435.5 kPa maximum peak pressure is obtained from single CMUT elements. Although there is some variation in pressure between CMUT elements of the array, minimum peak pressure is resulted to be 391.5 kPa. Thus, approximately 45 kPa of maximum difference between elements is obtained.

Normalized membrane displacement is shown in Figure 3.16 for 75 volts. Maximum physical membrane displacement is limited to gap height, t_g , and normalization is done according to the effective gap height, t_{ge} . Thus, the maximum swing that can be obtained for 7.5 MHz design is;

$$\max\left(\frac{x_p}{t_{ge}}\right) = \frac{t_g}{t_{ge}} = 0.806 \quad (3.4)$$

Above this maximum normalized value, the membrane will be touching the substrate in a tapping like motion instead of collapsing. However, since this motion will be increasing the backing loss, it is tried to be prevented and the plate motion remained in the uncollapsed region using the remaining gap size after static depression. Also by not giving any excitation voltages to the designed transducer, static depression caused by the atmospheric pressure is obtained where it is 1.503 nm, which is equal to 0.00877 normalized membrane displacement for every CMUT element for 7.5 MHz design.

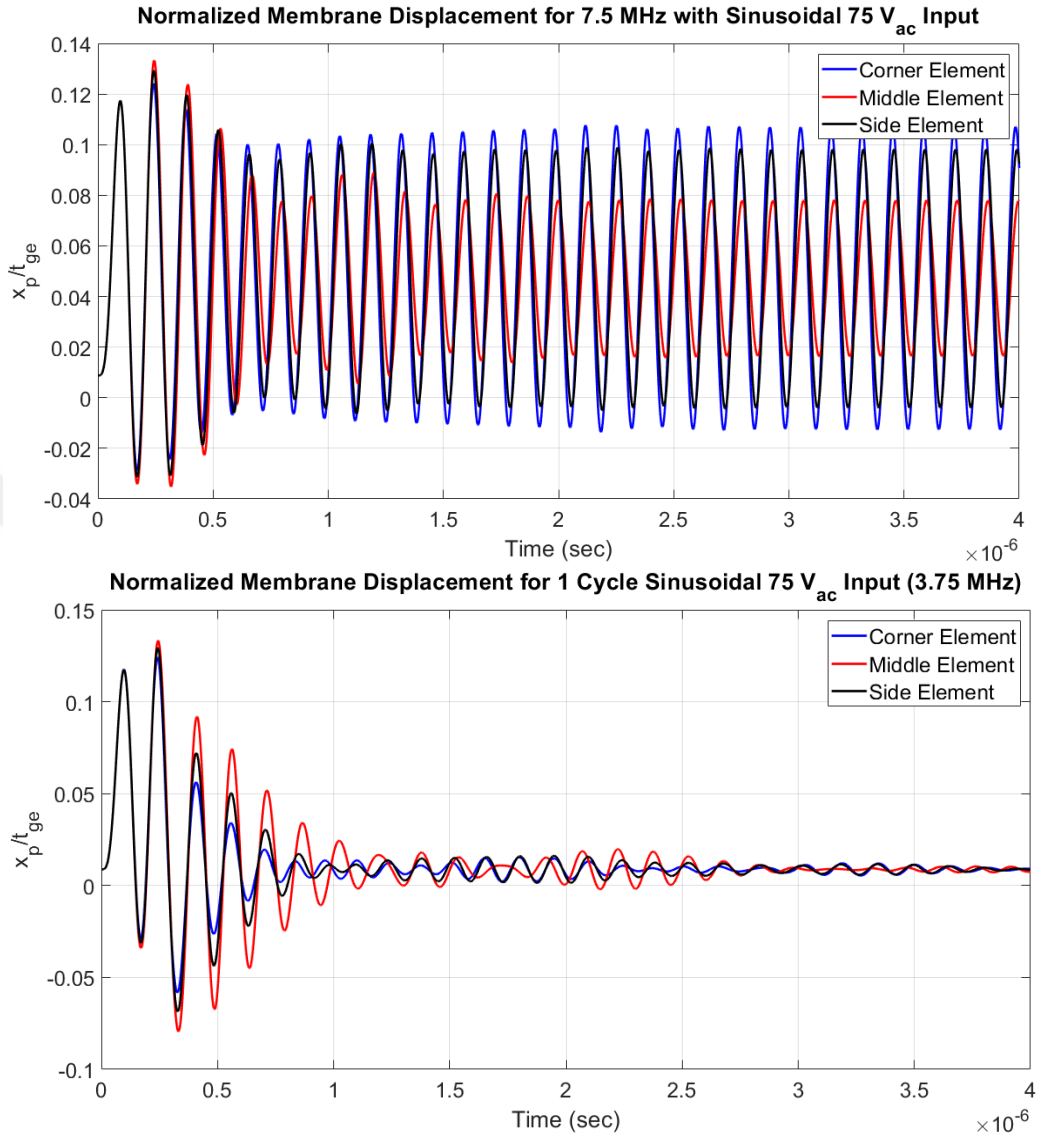


Figure 3.16: Normalized membrane displacement for 75 V_{ac} (a) transient and (b) one cycle sinusoidal input signal is obtained as 0.1072 and 0.1333 respectively.

Due to the numerous safety factors during the design process, with the specified gap height and given maximum operating voltage full swing of the membrane could not be maintained. Hence, the AC voltage is found for full swing with minimum voltage amplitude. This optimum mode of operation was referred as the minimum voltage mode (MVM) [39].

For a transient sinusoidal wave input MVM is simulated to be 149.2 V_{ac}. However, the full swing of the membrane is only maintained in the first cycle of

the input and then for the successive cycles the normalized membrane swing drops down to approximately 0.4. In order to avoid this, input voltage is given as a ramp function. By this way, MVM is increased to 188 volts. However, at this input voltage membrane can touch the substrate and so called *tapping* motion can be observed in the elements where it is located at the corner. It is called tapping since the membrane is not collapsing but bouncing back from the substrate periodically. The waveform generated in Section 3.5 Gaussian Enveloped Tone Burst Signal, is similar to the explained ramp function input where the MVM voltage can be increased significantly.

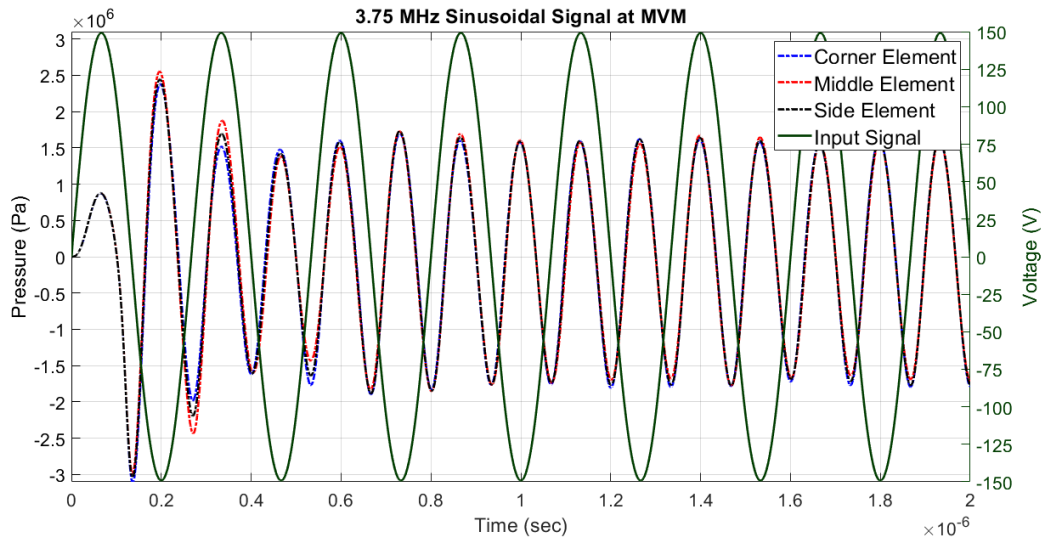


Figure 3.17: MVM voltage is found to be 149.2 V_{ac} with 1.673 MPa peak pressure acoustical output at steady state.

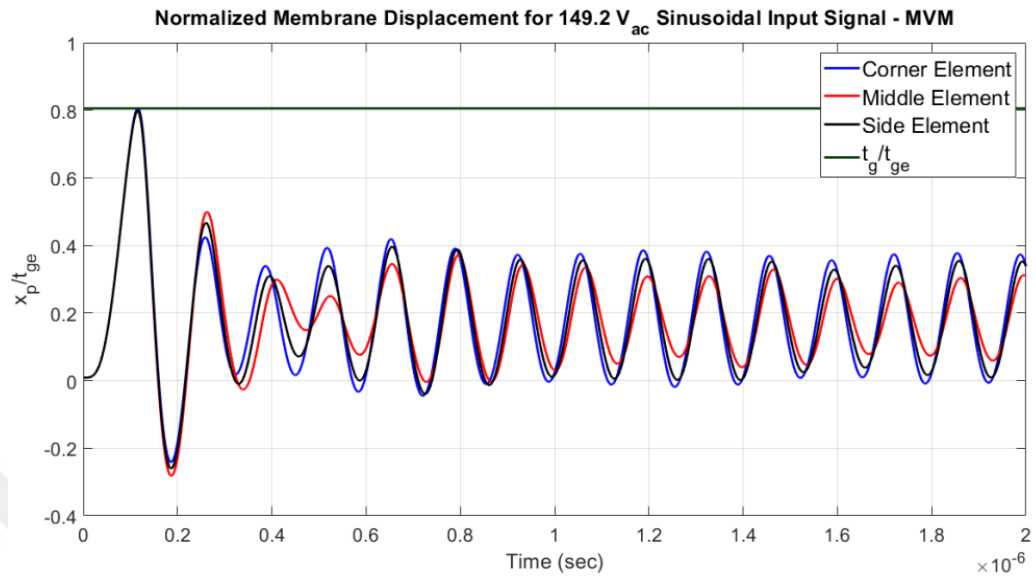


Figure 3.18: Normalized membrane displacement for MVM at 149.2 volts.

By using the same voltage for MVM, instead of transient sinusoidal waveform, 1 cycle of sinusoidal is given as input and particle velocity is observed.

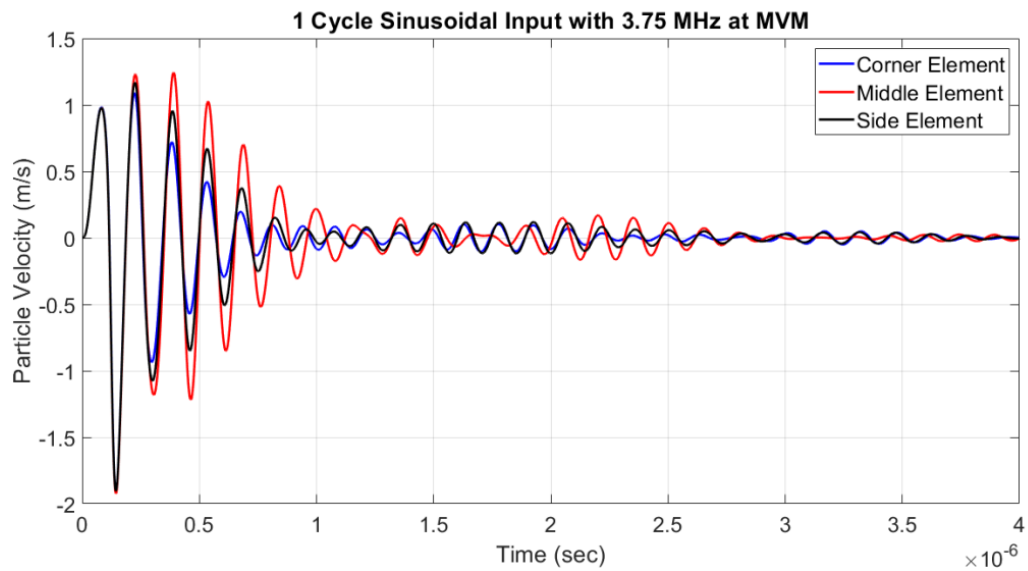


Figure 3.19: Particle velocity is observed at 3.75 MHz input frequency and input voltage levels of 149.2 V_{ac} (MVM) with one cycle sinusoidal waveforms. Two cycle of 7.5 MHz sine wave with 1.231 m/s peak velocity is obtained at acoustical output.

In Chapter 3.2 Harmonic Balance Analysis, peak frequency is explained and found to be 6.36 MHz. At this frequency transient analysis with transient and one cycle of input with 75 volt is given and pressure outputs are shown. Although the waveform is only different by settling into steady state in longer period, the narrow-band structure of the frequency domain solution makes it undesirable to operate the transducer at this frequency but larger acoustical pressure output can be obtained coherently to the harmonic balance analysis.

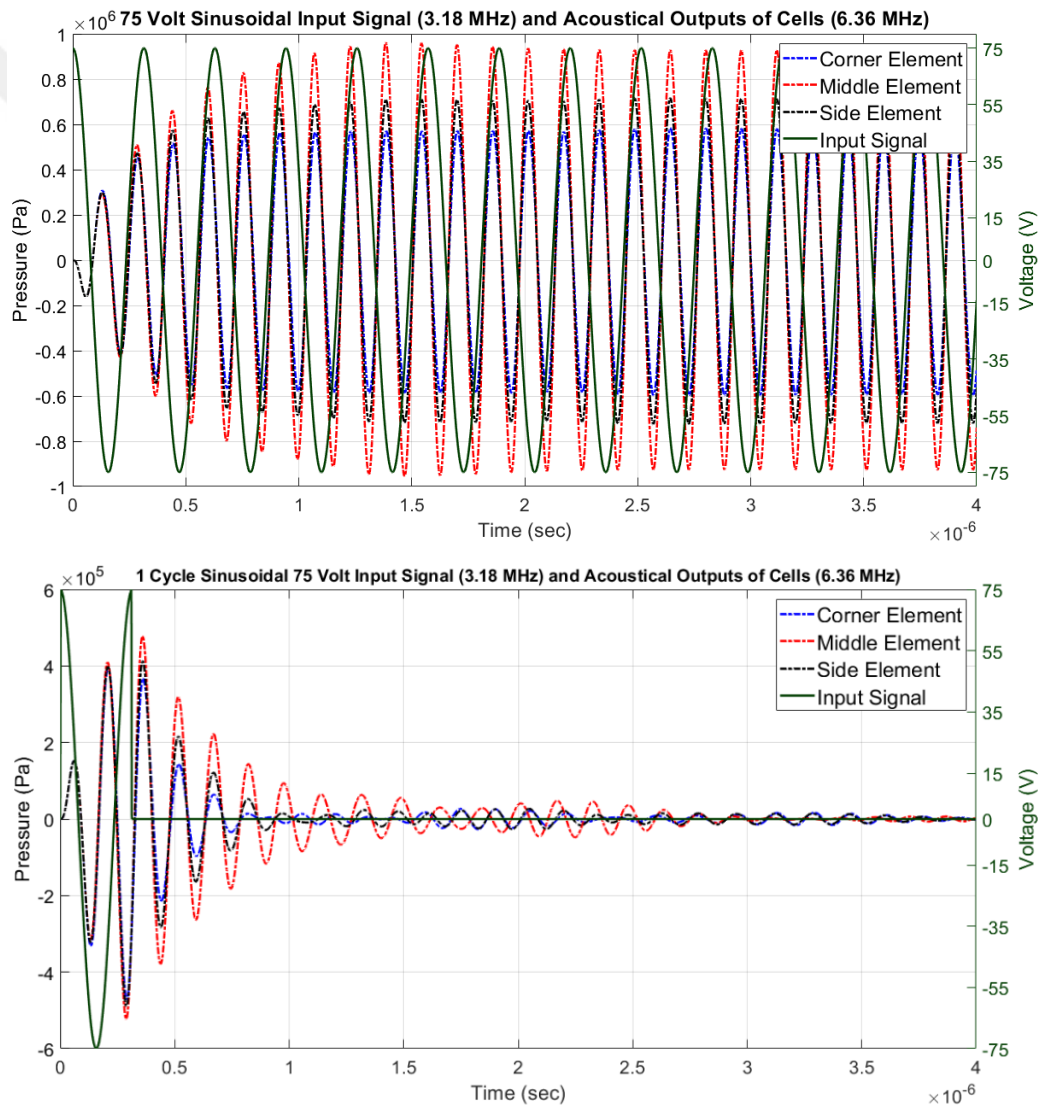


Figure 3.20: Transient analysis at peak frequency of 3.18 MHz electrical input and 6.36 MHz acoustical output. 75 volts of (a) Transient sinusoidal input

resulted in 927.5 kPa peak pressure and (b) 1 cycle sinusoidal input is resulted in 492 kPa peak pressure.

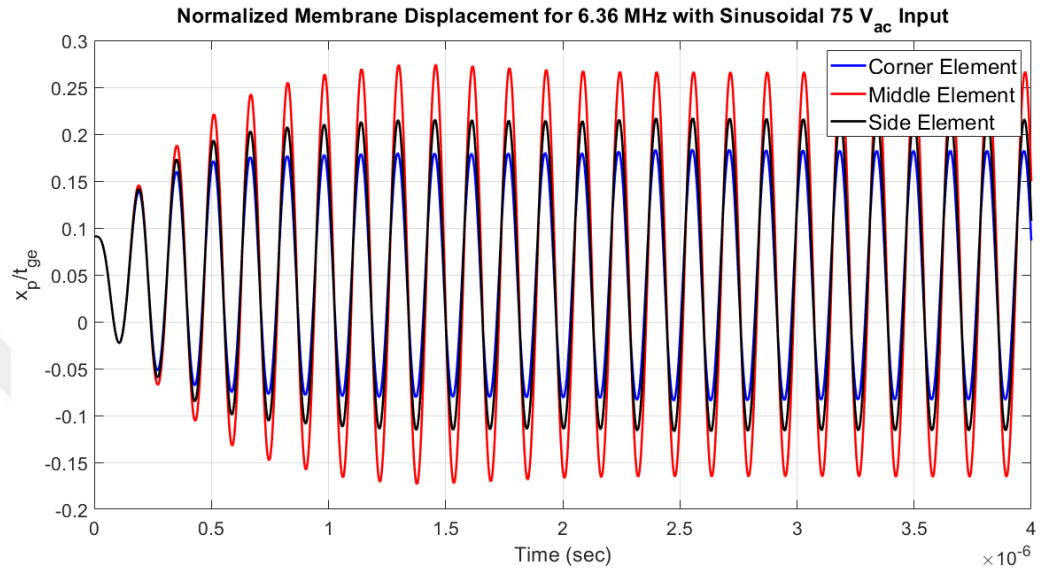


Figure 3.21: Peak normalized membrane displacement at steady state is obtained as 0.2728 at peak frequency with 75 V_{ac}.

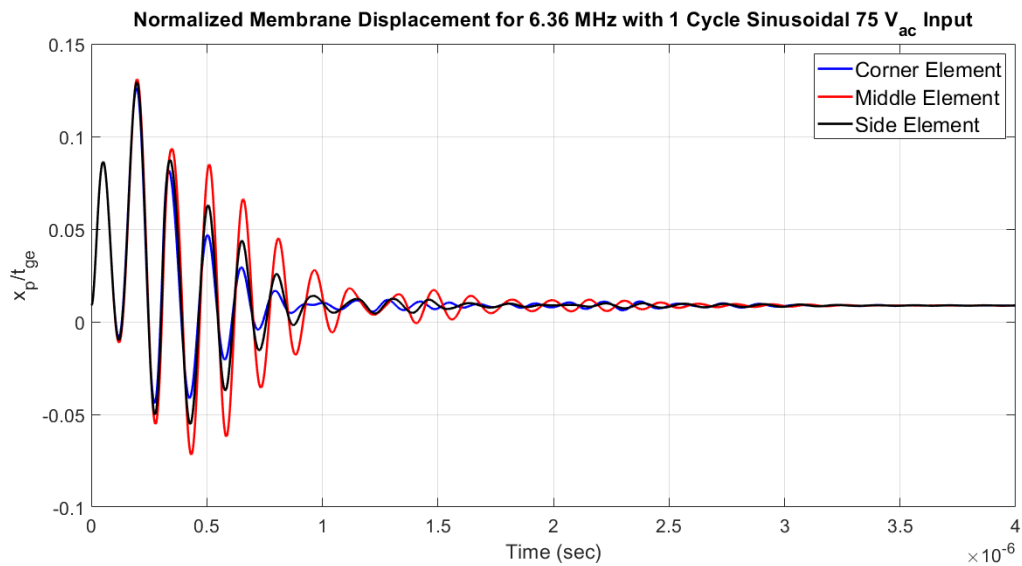


Figure 3.22: Particle velocity is observed at peak frequency of 3.18 MHz input frequency and input voltage levels of 75 V_{ac} with one cycle sinusoidal waveforms. At acoustical output 0.3065 m/s peak velocity is obtained.

Finally, sinusoidal wave inputs are given with different cycles (0.5, 1, and 4 input cycles) at 3.75 MHz (half of the acoustical operation frequency) and two different voltage levels (5 and 75 volts). As a result, both the electrical input frequency and the given cycles are doubled. Particle velocity observed for 1 cycle of sinusoidal input is also shown.

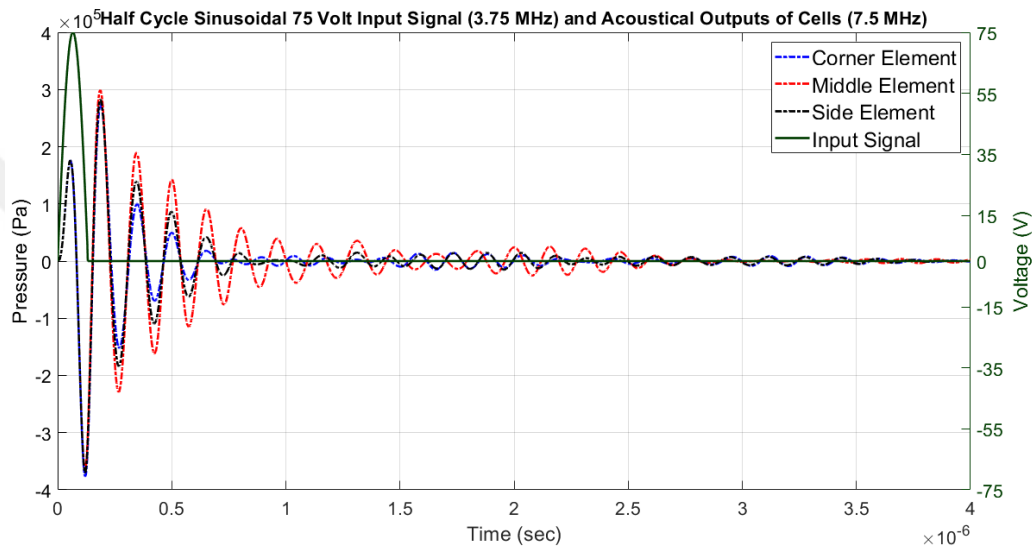


Figure 3.23: Transient analysis at 3.75 MHz input frequency and input voltage level of 75 volts with half cycle sinusoidal waveforms. One cycle of 7.5 MHz sine wave with 299 kPa peak pressure is obtained at acoustical output.

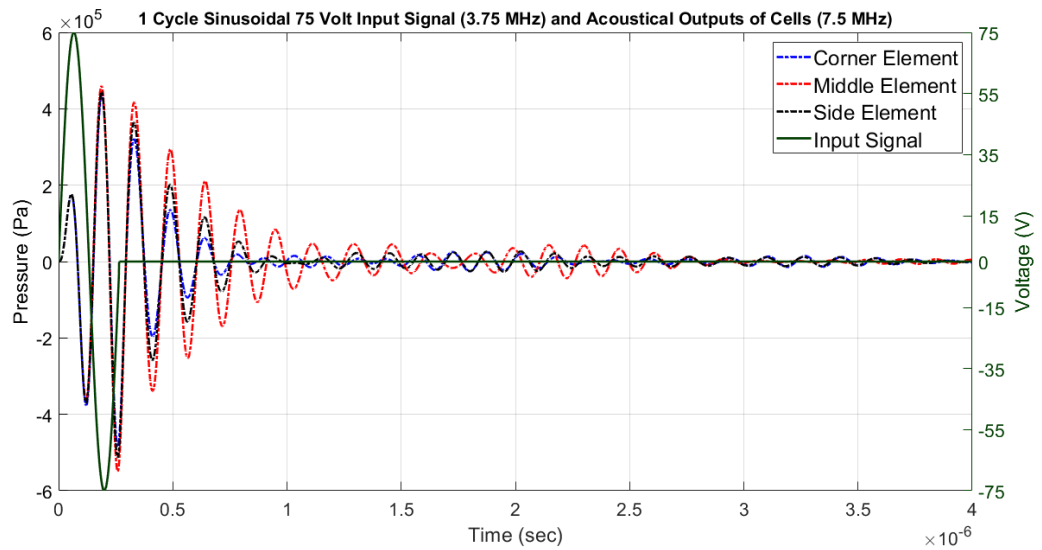


Figure 3.24: Transient analysis at 3.75 MHz input frequency and input voltage levels of 75 volts with one cycle sinusoidal waveforms. Two cycle of 7.5 MHz sine wave with 459.9 kPa peak pressure is obtained at acoustical output.

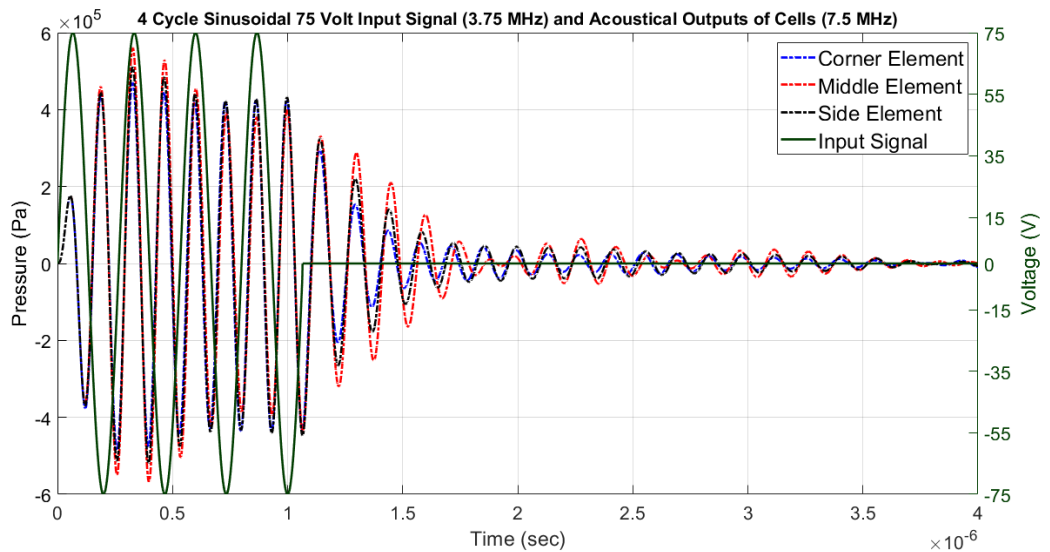


Figure 3.25: Transient analysis at 3.75 MHz input frequency and input voltage levels of 75 volts with four cycle sinusoidal waveforms. Eight cycles of 7.5 MHz sine wave with 560.7 kPa peak pressure is obtained at acoustical output.

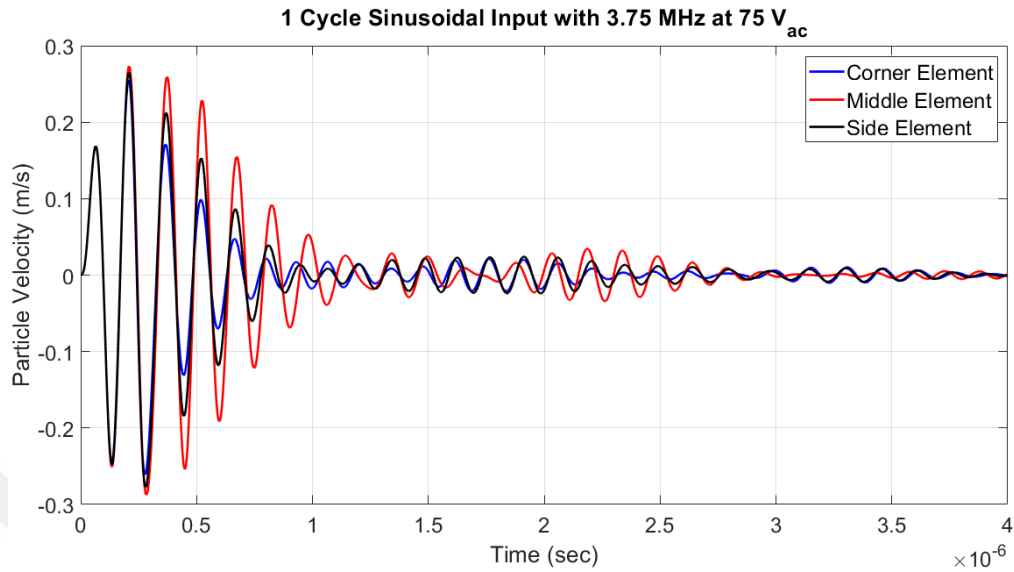


Figure 3.26: Particle velocity is observed at 3.75 MHz input frequency and input voltage levels of 75 volts with one cycle sinusoidal waveforms. Two cycle of 7.5 MHz sine wave with 0.2732 m/s peak velocity is obtained at acoustical output.

3.5 Gaussian Enveloped Tone Burst Signal

In biomedical ultrasound, Gaussian enveloped tone burst signals are widely used for transmission [40]. Since the area of application for these transducer designs is biomedical, it is also necessary to obtain transient results for Gaussian enveloped tone burst signal transmissions.

Gaussian enveloped tone burst signals are generated in ADS by multiplying the sinusoidal signals with appropriate pulse function by adjusting the rise and fall times of the pulse. For rise, fall and width durations of the pulse 1.5 cycle of the electrical input frequency is given, where it is equal to 400 ns for 3.75 MHz in order to operate at 7.5 MHz at the acoustical output. By this way 5 cycles of Gaussian enveloped tone burst signal is obtained at the electrical input and 10 cycles of Gaussian enveloped tone burst signal with twice the frequency of the input at the acoustical output.

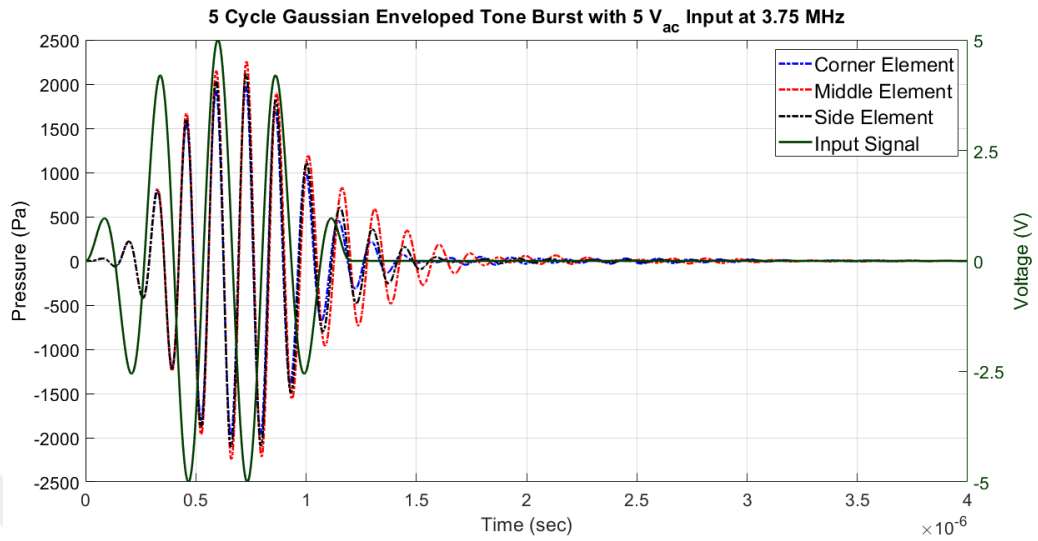


Figure 3.27: Transient analysis at 3.75 MHz input frequency and input voltage level of 5 volts with 5 cycle Gaussian enveloped tone burst signal. 10 cycle of 7.5 MHz Gaussian enveloped tone burst signal with 2.256 kPa peak pressure is obtained at acoustical output.

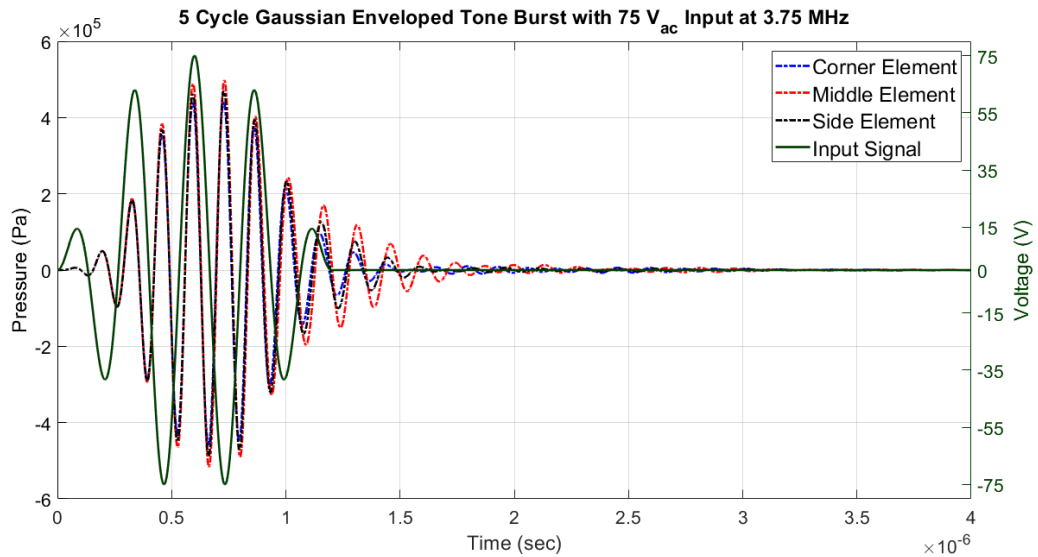


Figure 3.28: Transient analysis at 3.75 MHz input frequency and input voltage level of 75 volts with 5 cycle Gaussian enveloped tone burst signal. 10 cycle of 7.5 MHz Gaussian enveloped tone burst signal with 498.1 kPa peak pressure is obtained at acoustical output.

While obtaining 2.256 kPa peak pressure from single CMUT elements when 5 V_{ac} input is given, the peak pressure is increased to 498.1 kPa peak pressure when the input voltage is increased to 75 V_{ac}, which is the maximum output voltage of DiPhAS.

Normalized membrane displacement is analysed similarly to the transient sinusoidal wave simulations with 75 V and 3.75 MHz input. It is measured that the maximum normalized membrane displacement is 0.1132, which equals to 19.4 nm peak deflection with given voltage.

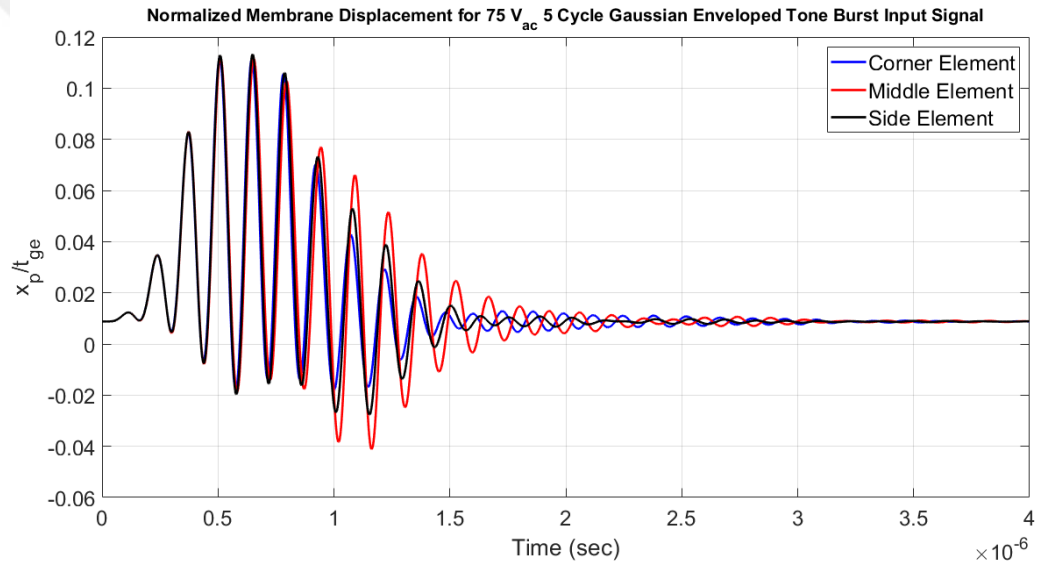


Figure 3.29: Normalized membrane displacement for 75 V_{ac} 5 cycle of Gaussian enveloped tone burst input signal at operation frequency of 3.75 MHz.

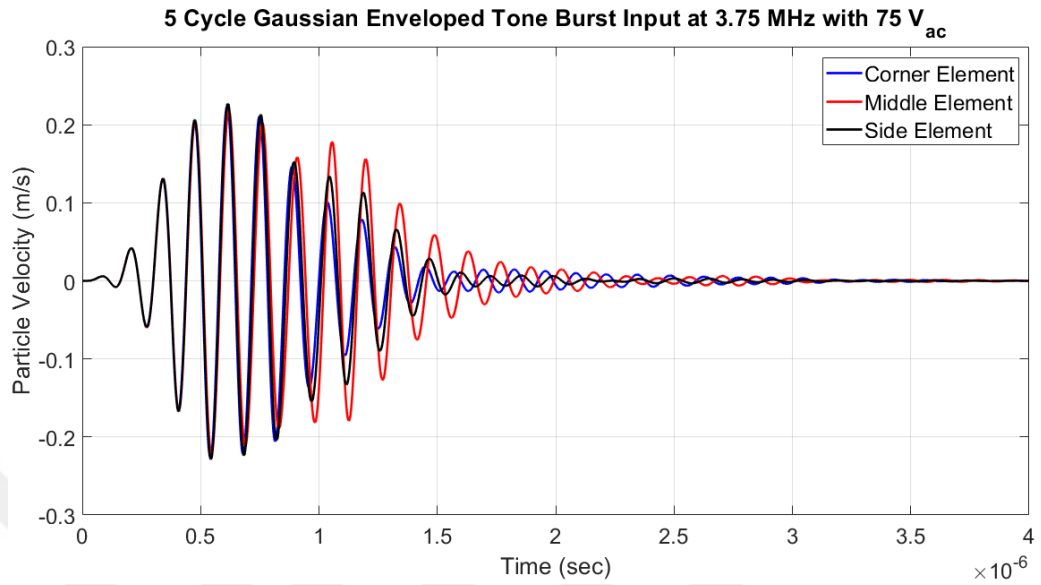


Figure 3.30: Maximum peak particle velocity for $75 V_{ac}$ 5 cycle of Gaussian enveloped tone burst input signal at operation frequency of 3.75 MHz is found to be 0.2272 m/s.

Also the MVM voltage level is found to be $186.15 V_{ac}$ for specified 5 cycle Gaussian enveloped tone burst with 3.75 MHz signal input. Due to the smoothed nature of Gaussian enveloped tone burst function, membrane displacement is also smoothed and maximum displacement can be mostly maintained throughout the electrical input transmission phase length. Hence, unlike the transient sinusoidal input maximum membrane displacement does not drop down immediately after the first cycle.

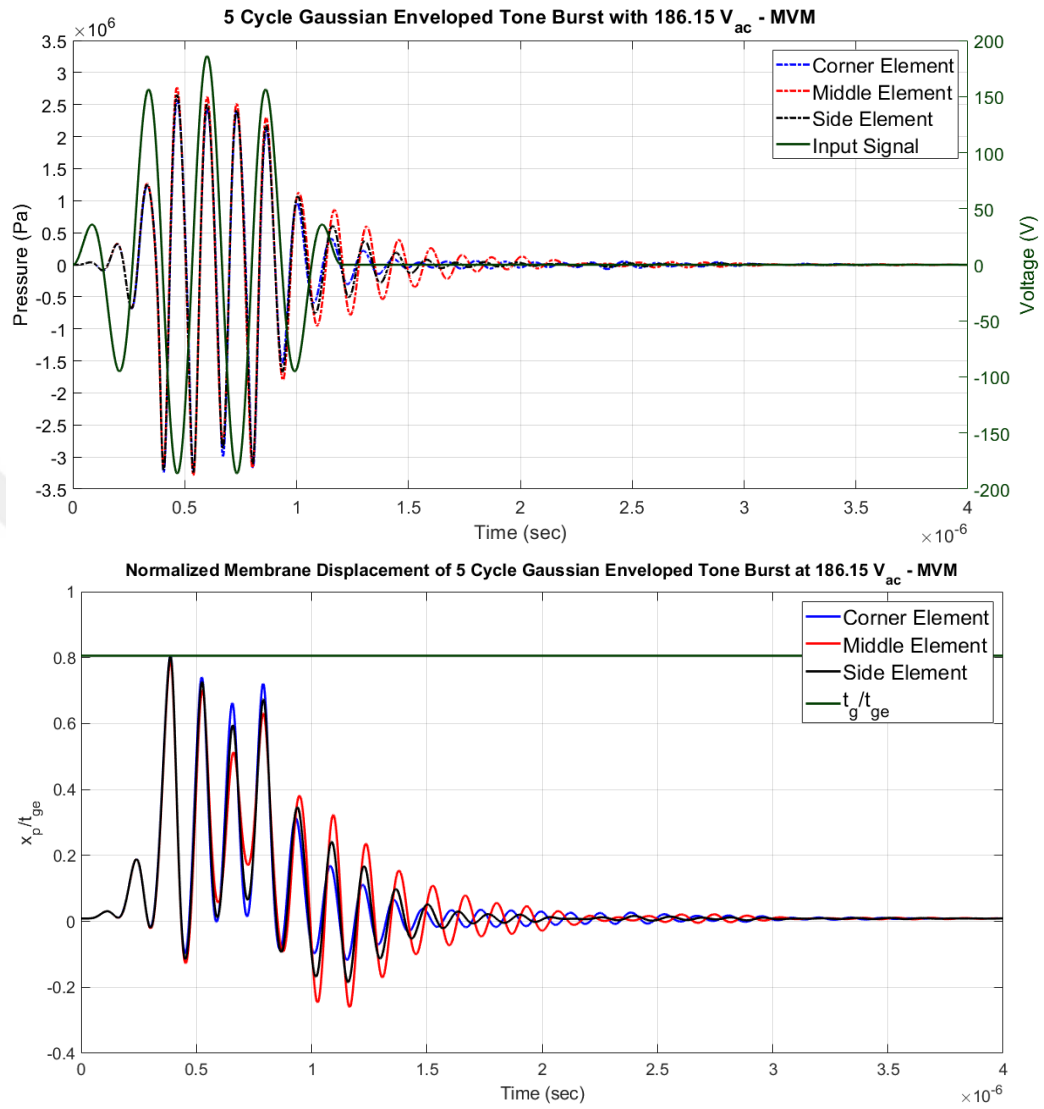


Figure 3.31: (a) Peak pressure of 2.764 MPa of acoustical output is obtained at MVM with 186.15 V_{ac}. (b) Normalized membrane displacement is calculated for MVM.

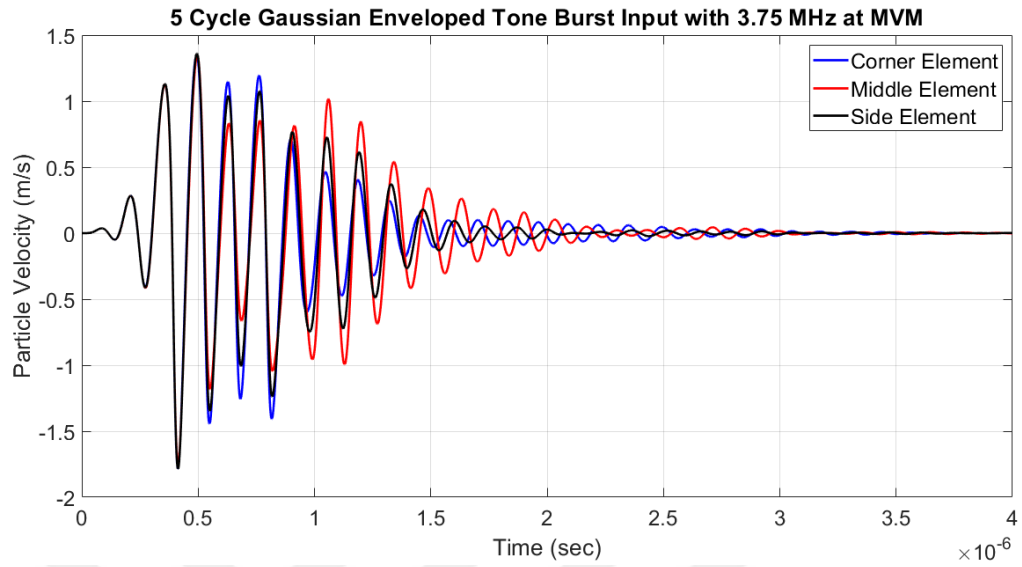


Figure 3.32: Maximum peak particle velocity for 186.15 V_{ac} (MVM) 5 cycle of Gaussian enveloped tone burst input signal is found to be 1.362 m/s.

Finally, Gaussian enveloped tone burst waveform is also applied at peak frequency, 3.18 MHz at electrical input and 6.36 MHz at acoustical output. Waveform is constructed with the same specifications and 5 cycle input with 75 V_{ac} resulted in 10 cycle Gaussian enveloped tone burst output at 6.36 MHz.

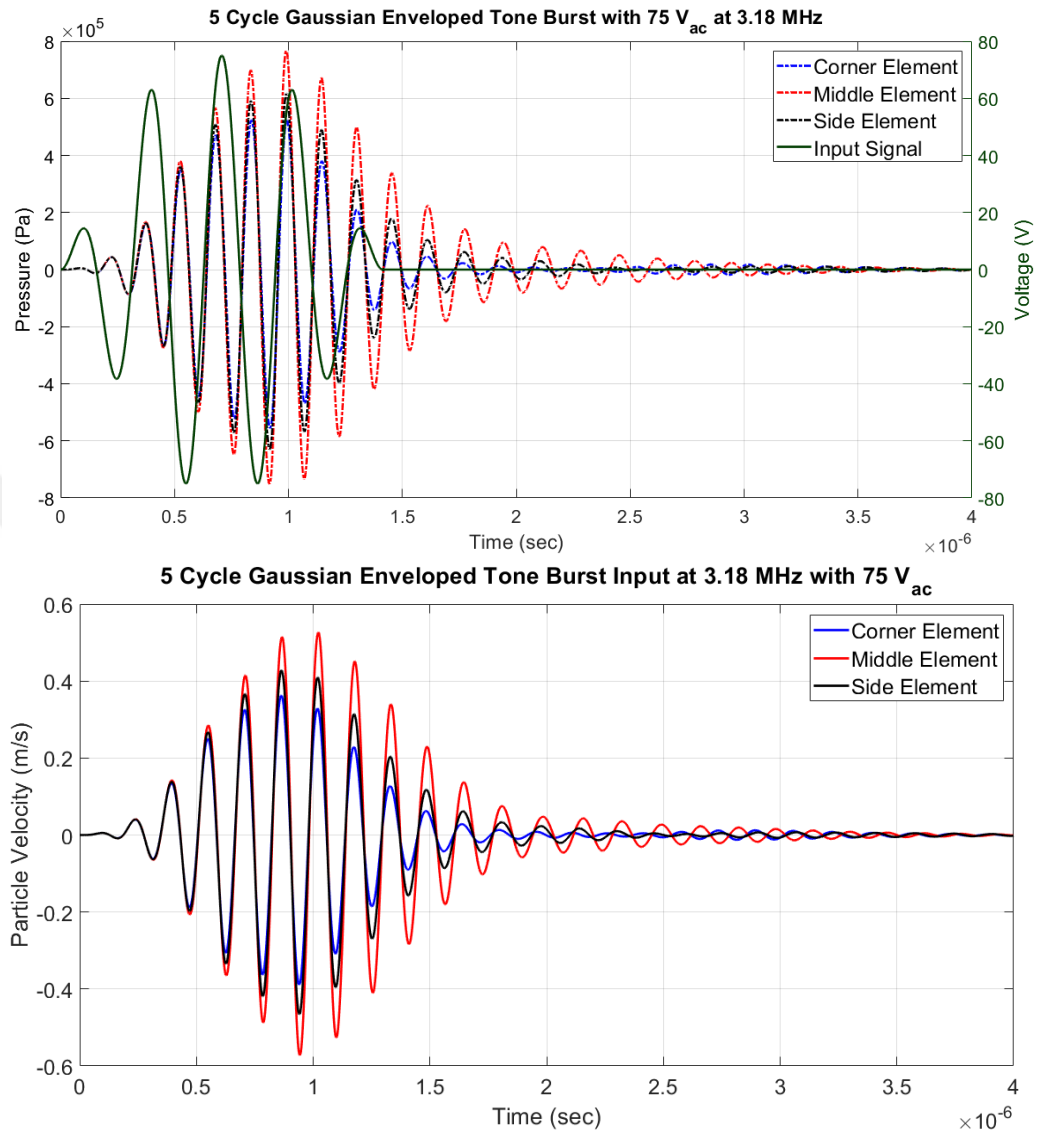


Figure 3.33: 5 cycle Gaussian enveloped tone burst signal is driven at peak frequency of 3.18 MHz with 75 V_{ac}. (a) 807.4 kPa peak pressure is obtained at acoustical output with ten cycle Gaussian enveloped tone burst signal at 6.36 MHz. (b) Maximum peak particle velocity for 75 V_{ac} 5 cycle of Gaussian enveloped tone burst input signal at peak frequency of 3.18 MHz is found to be 0.5268 m/s.

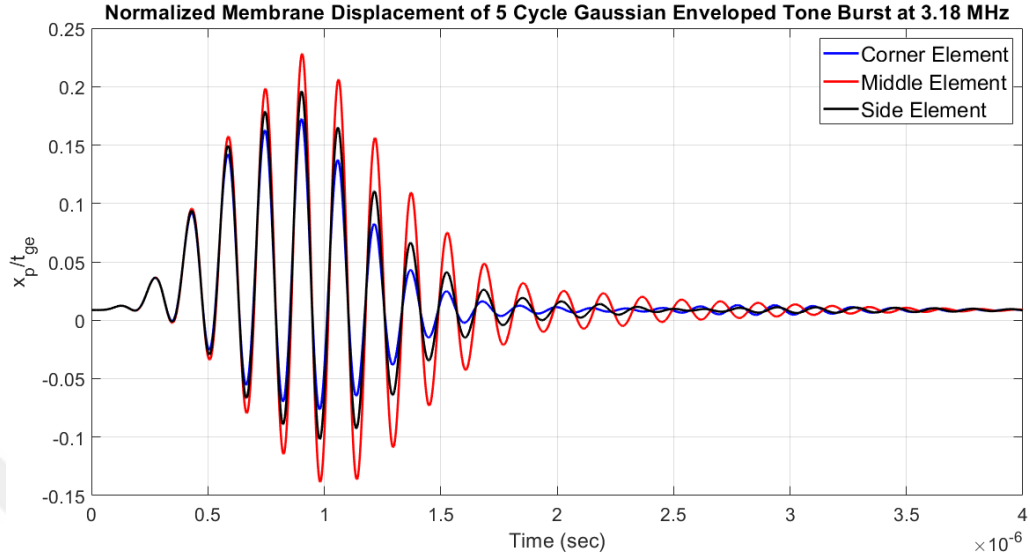


Figure 3.34: Maximum peak normalized membrane displacement is found to be 0.2415 for peak frequency input of 5 cycle Gaussian enveloped tone burst signal.

3.6 Pulse Width Modulation (PWM)

Using arbitrary waveforms for ultrasonic signal transmission generated by PWM modulation is presented earlier. By this way coded signals can be generated and used for transmission for higher signal-to-noise ratio [41]. Complementary Golay coded signals can be used for this purpose in further studies with this designed transducer [42]. The ultrasound measurement system, DiPhAS, has the capability of using tri-state PWM signals for transmission.

Another advantage of using PWM signals at unbiased mode of operation is that higher resolution signals can be obtained at acoustic output for higher frequencies. By using the same time domain step size, which is usually determined by the clock frequency of the FPGA that generates the transmission waveform, generation of lower frequencies can be obtained with higher resolution due to the higher clock rate ratio. In the case of DiPhAS, clock frequency of the FPGA is 480 MHz, thus the time domain step size is

approximately 2.0833 ns. With this step size resolution of PWM signal for 3.75 MHz is higher than 7.5 MHz.

In order to examine the feasibility of PWM signals using this mode of operation, bit sequenced input source is used in ADS. Bit sequences with tri-state PWM signals are generated through MATLAB Simulink. Since in ADS these bit sequences could be generated between two voltage levels, positive and negative cycles of this signal are generated separately and fed into separate input sources. Positive and negative cycle sources are summed in ADS and given as electrical input to CMUTs individually. For simplicity, PWM signals are generated to output sinusoidal waveform at operation frequencies.

After constructing the simulation elements, transient analyses are done with two different voltage levels (5 and 75 V) and different cycles. In each figure that includes the input signal, discontinuities are shown with red circles in order to express that the PWM input signals are not ordinary square signals but tri-state pulse-width modulated signals that are generated in MATLAB. Simulation results for 5 V_{ac} input voltage is shown in Appendix B.1 Extra Simulation Graphics. Firstly, transient PWM signal simulations are conducted.

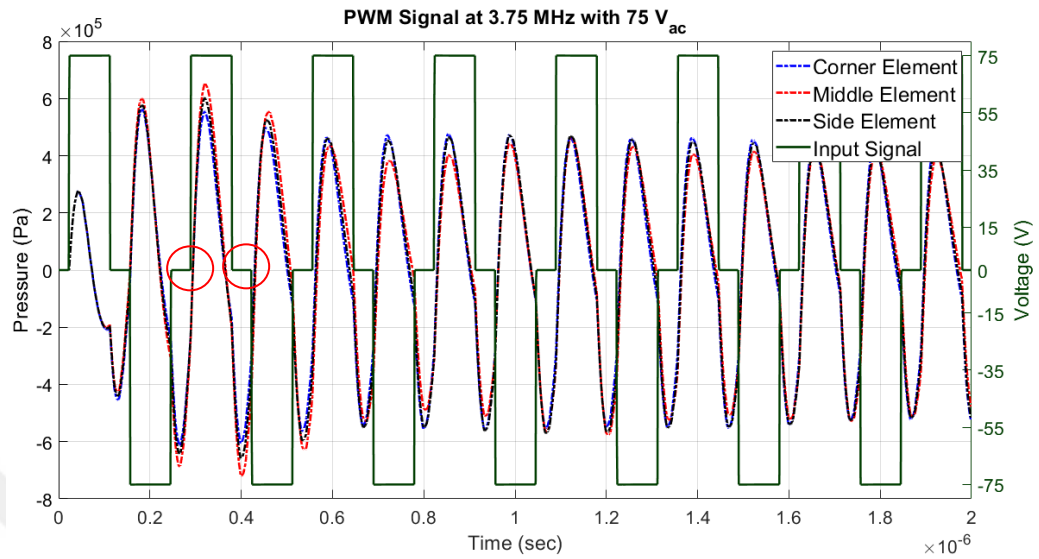


Figure 3.35: Transient PWM signal is given as input at 3.75 MHz with 75 V_{ac} . Sinusoidal waveform is resulted at acoustical output with 7.5 MHz and 456.5 kPa peak pressure at steady state.

Then simulations are repeated with different cycles. Half, one and four cycles of 3.75 MHz PWM signals are given as input at 75 V_{ac} and one, two and eight cycles of 7.5 MHz sinusoidal signals are resulted at the acoustical output of the transducer elements.

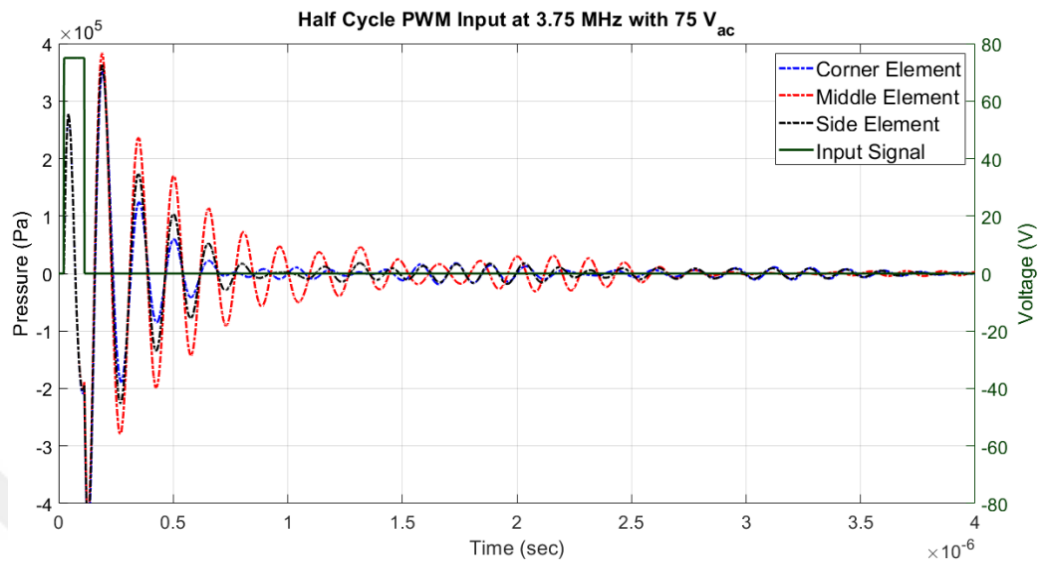


Figure 3.36: Transient analysis at 3.75 MHz input frequency and input voltage levels of 75 volts with half cycle PWM signal. One cycle of 7.5 MHz sinusoidal wave with 383.2 kPa peak pressure is obtained at acoustical output.

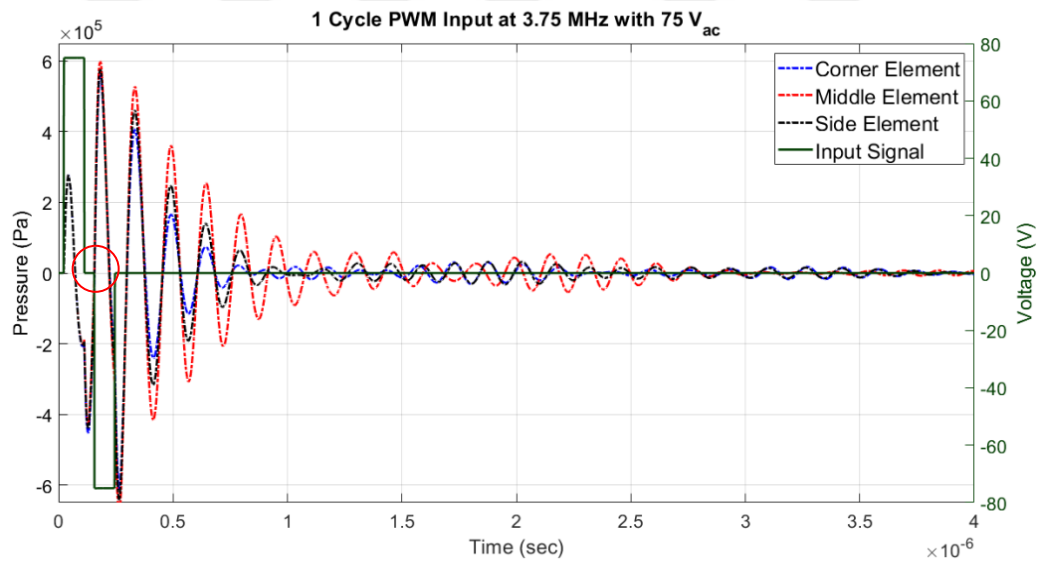


Figure 3.37: Transient analysis at 3.75 MHz input frequency and input voltage levels of 75 volts with one cycle PWM signal. Two cycle of 7.5 MHz sinusoidal wave with 598.9 kPa peak pressure is obtained at acoustical output.

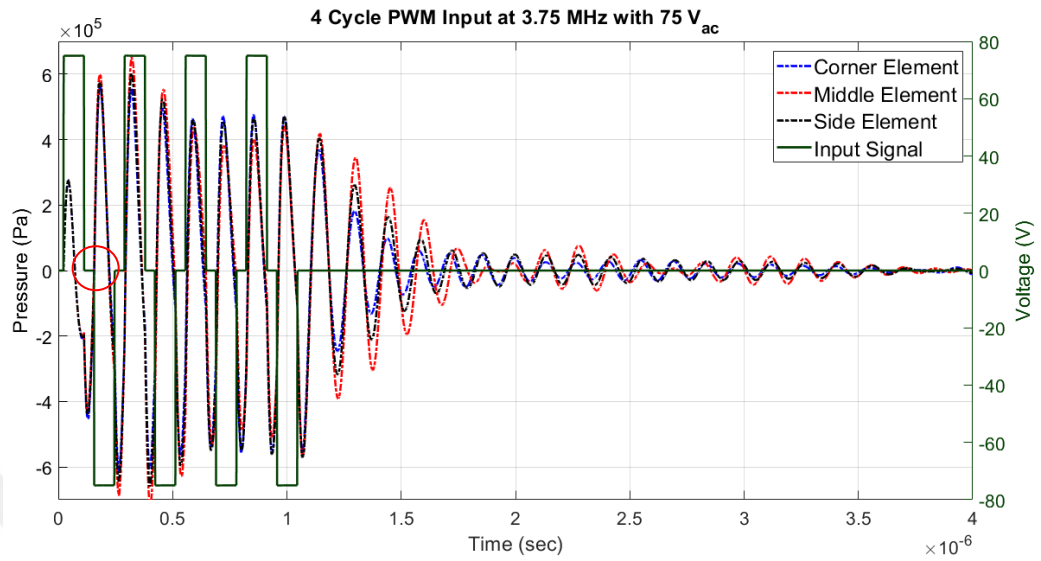


Figure 3.38: Transient analysis at 3.75 MHz input frequency and input voltage levels of 75 volts with four cycle PWM signal. Eight cycle of 7.5 MHz sinusoidal wave with 651.9 kPa peak pressure is obtained at acoustical output.

After obtaining the pressure outputs, normalized membrane displacement is also examined for transient and 1 cycle PWM signals with 75 V_{ac} at 3.75 MHz.

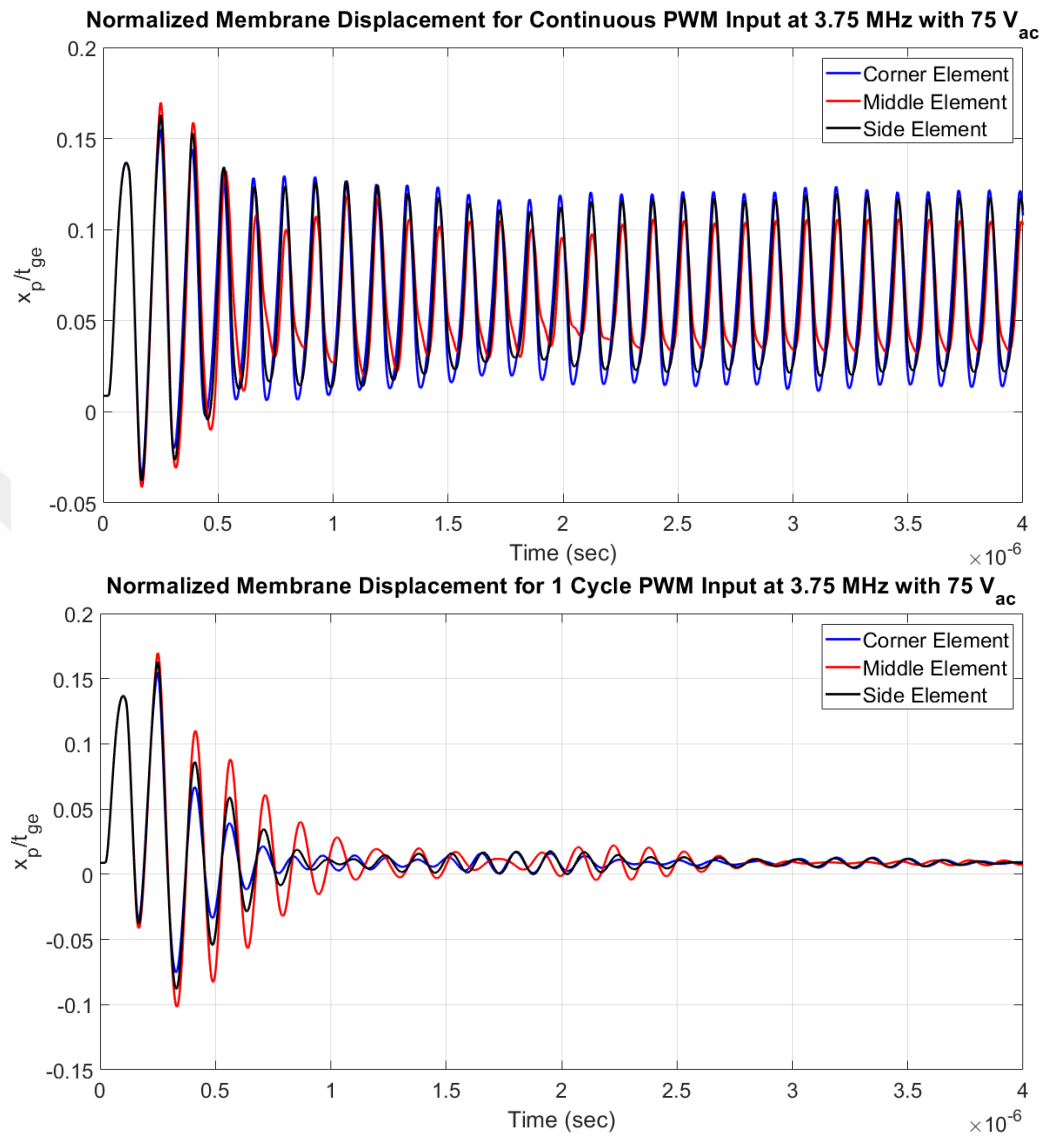


Figure 3.39: Normalized membrane displacement for (a) transient and (b) 1 cycle of PWM signal input. Peak normalized membrane displacement for both transmissions are simulated to be 0.1697.

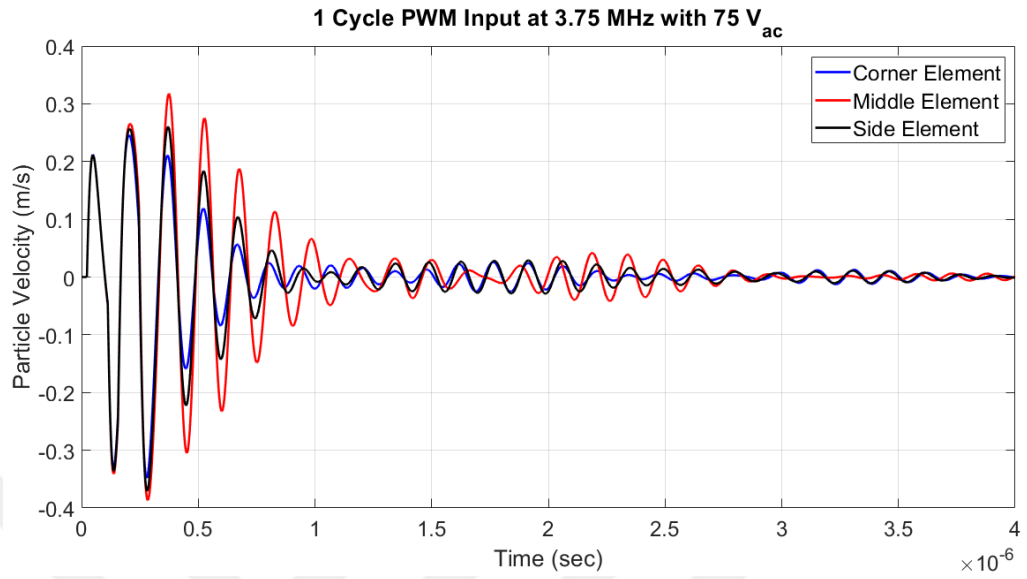


Figure 3.40: Maximum peak particle velocity for $75 V_{ac}$ 1 cycle PWM input signal at operation frequency of 3.75 MHz is found to be 0.3175 m/s.

Also for PWM signal transmission MVM is found to be $131 V_{ac}$. Maximum swing is obtained at this voltage level for PWM input signals, which the voltage level is lower compared to the other transmitted waveforms. Normalized membrane displacement for one cycle PWM input at MVM is also shown.

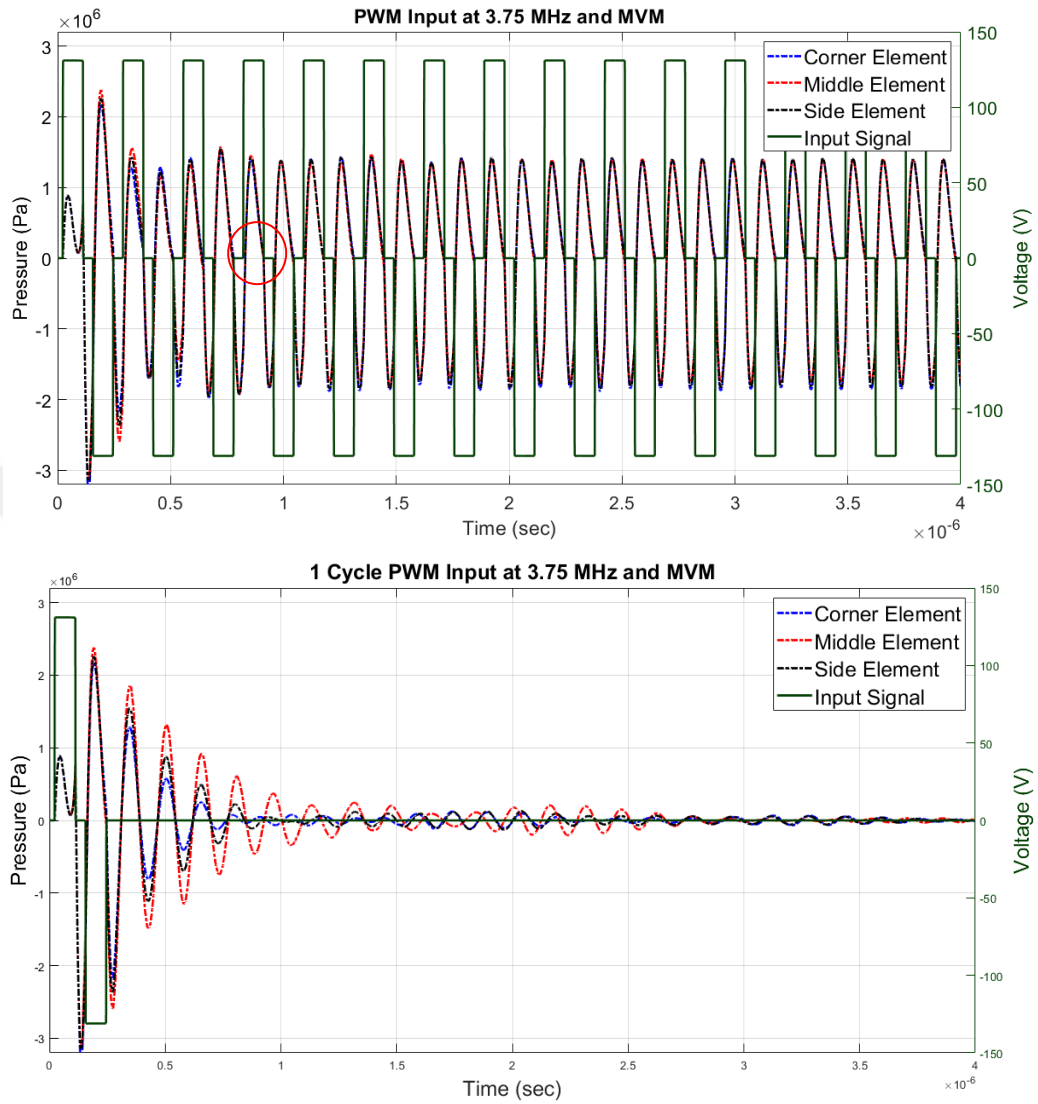


Figure 3.41: Transducer is driven at MVM with 131 V_{ac}. With (a) transient PWM input 1.383 MPa peak pressure is obtained at steady state. For (b) 1 cycle transmission of PWM signal, 2.381 MPa of peak pressure is obtained.

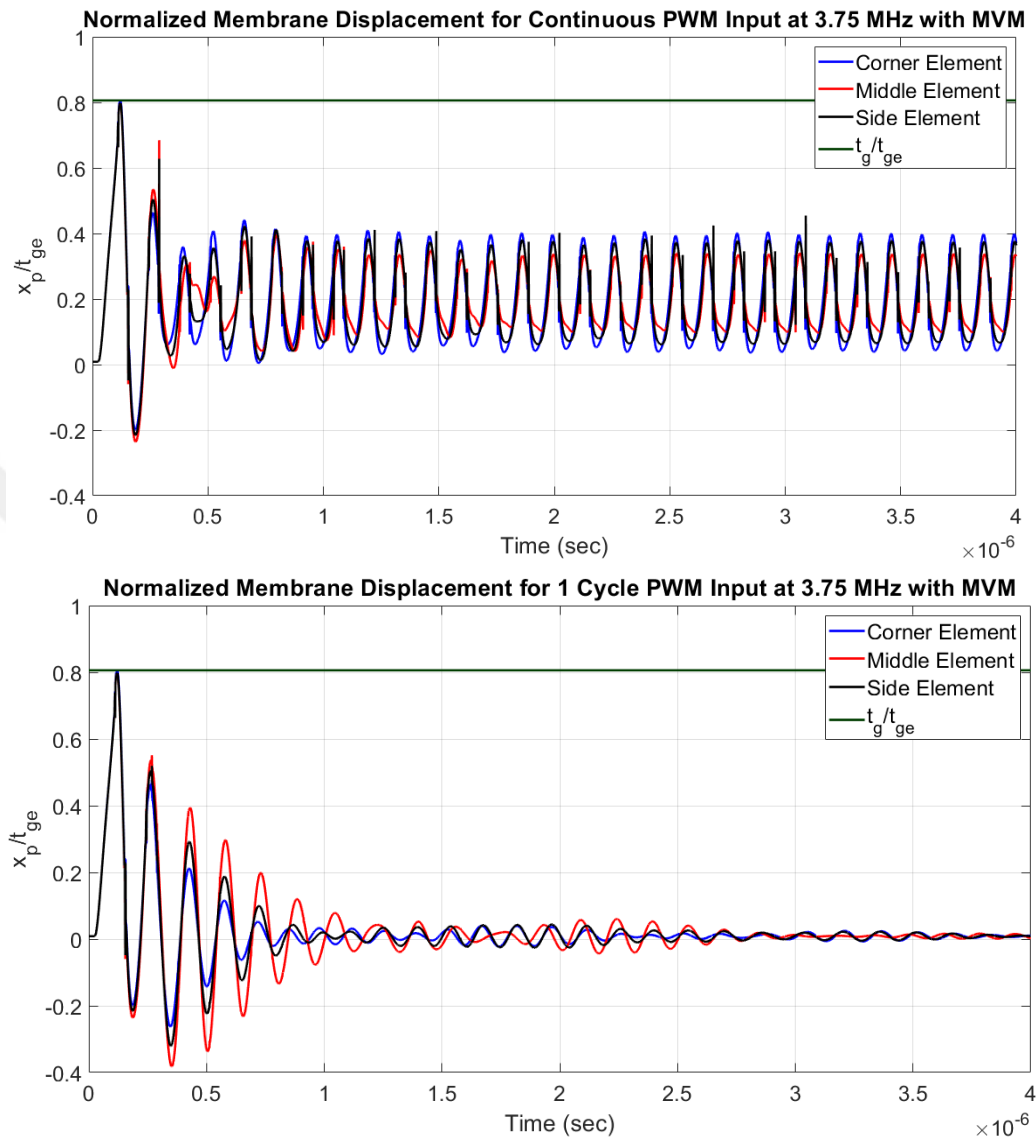


Figure 3.42: Normalized membrane displacement for (a) transient and (b) one cycle PWM input at 3.75 MHz with MVM.

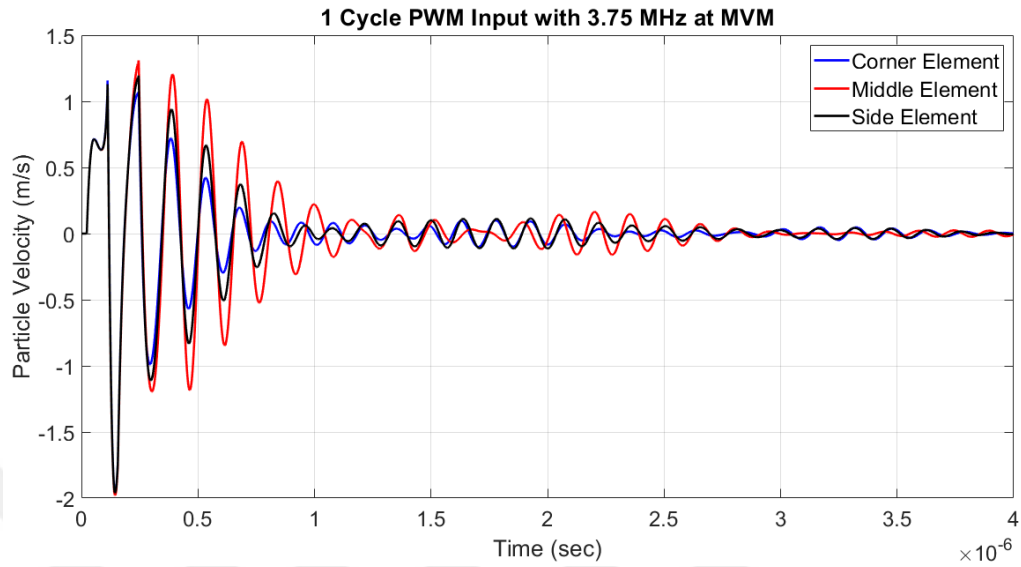


Figure 3.43: Maximum peak particle velocity for 131 V_{ac} (MVM) 1 cycle PWM input signal at operation frequency of 3.75 MHz is found to be 1.31 m/s.

Similarly to the previous simulations, peak frequency of 3.18 MHz at the electrical input is used to observe the effect of this resonance with the use of PWM signals. It is observed that resulting acoustical output is similar to the obtained results in previous peak frequency simulations. Sinusoidal signal with slow rising time at 6.36 MHz is obtained at the acoustical output. At this input frequency, pressure outputs, membrane displacements and particle velocity are observed.

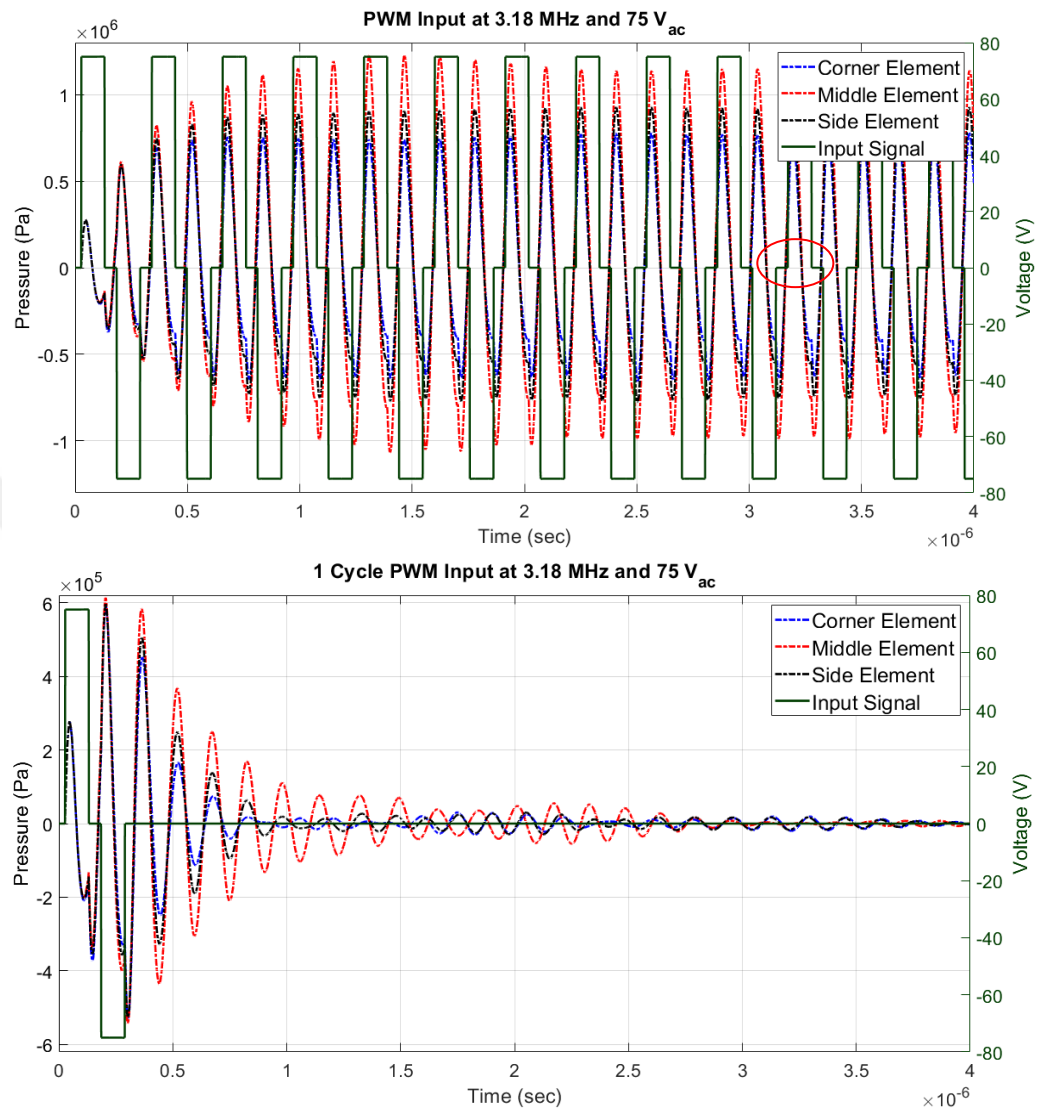


Figure 3.44: Transducer is driven at peak frequency of 3.18 MHz with 75 V_{ac}. With (a) transient PWM input 1.178 MPa peak pressure is obtained at steady state. For (b) 1 cycle transmission of PWM signal, 613.1 kPa of peak pressure is obtained.

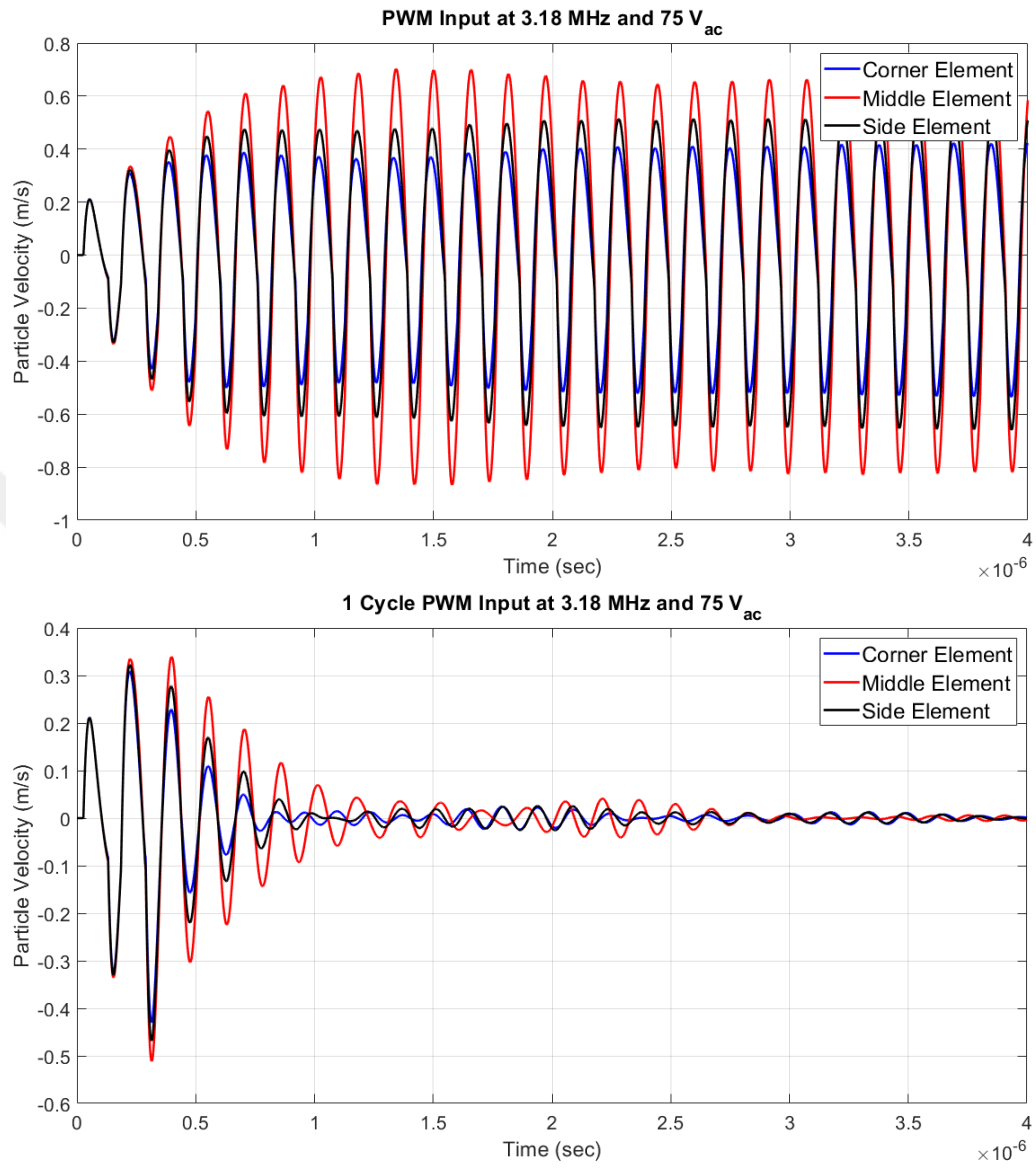


Figure 3.45: With (a) transient PWM input 0.6626 m/s peak particle velocity is obtained at steady state. For (b) 1 cycle transmission of PWM signal, 0.3352 m/s of peak particle velocity is obtained.

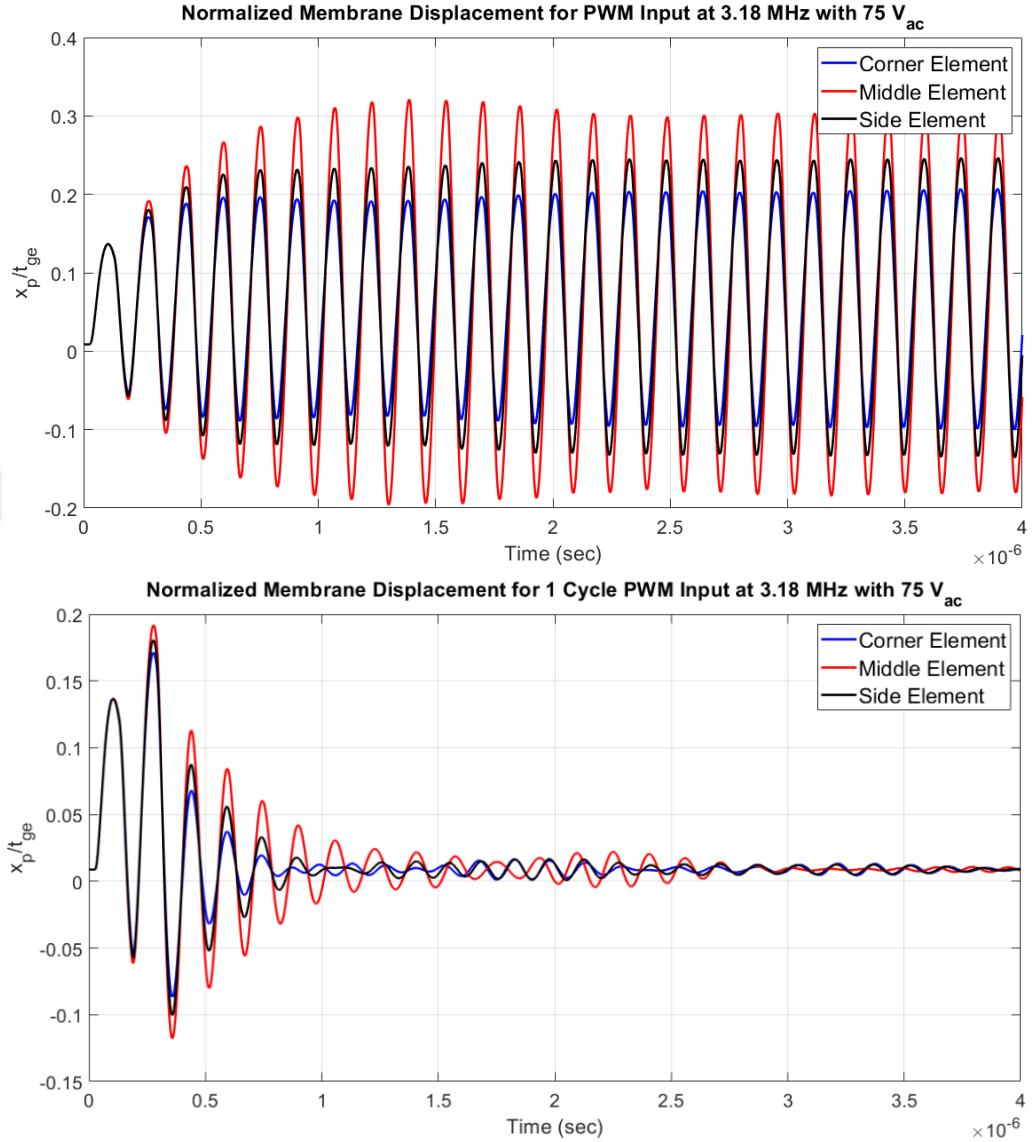


Figure 3.46: With (a) transient PWM input, peak normalized membrane displacement is obtained as 0.3034 at steady state. For (b) 1 cycle transmission of PWM signal, peak normalized membrane displacement is obtained as 0.1918.

3.7 Radiation Pattern Simulations

Throughout the design process of the transducers discussed in this work, radiation pattern, side lobe level and Rayleigh distance was the starting point of the design procedure and could be applied to any desired application accordingly. Hence, simulating the radiation pattern and validating the design parameters is an important step in this work.

In order to simulate the radiation pattern of the designed transducer in an appropriate approach, MATLAB toolbox k-wave is used for this purpose [43]. Since k-wave toolbox is a FEM based analytic simulation tool, a simulation space consisting of the relevant elements and medium has to be determined [44]. Simulation space is constructed by using square cube shaped grids with dimensions of meter units. For an accurate and precise simulation these grid dimensions have to be determined correspondingly. Choosing smaller values for grid dimensions will increase the accuracy of the simulation results, on the other hand, smaller dimensions results in highly increased simulation durations. Thus, the dimensions need to be selected optimally in order to have an efficient simulation result with acceptable durations.

For this purpose firstly the transducer dimensions for 7.5 MHz operation frequency design is considered. The smallest dimension in this design is the spacing between consecutive CMUT elements with 32 μm width. Diameter of the CMUT element is 160 μm , which is exactly five times of the spacing. Thus, the grid dimensions are determined to be 32 μm (one side of the cube) and the whole transducer is constructed in k-wave accordingly. Since each grid point (voxel) can be used as transmitter or receiver, in this case each 5 $\times$ 5 grid point indicates one CMUT element. Although circle shape cannot be maintained, by using appropriate pressure amplitudes, circle shape is imitated.

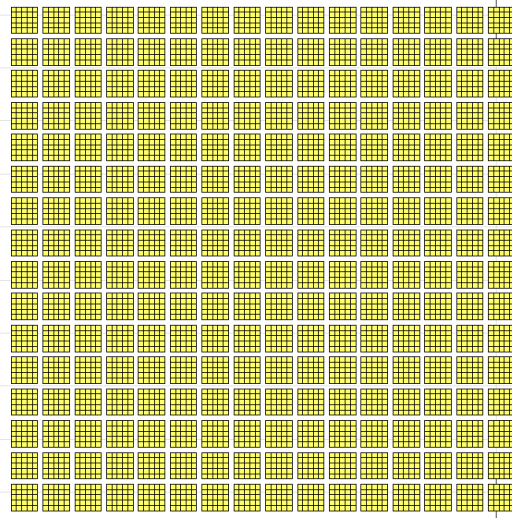


Figure 3.47: Orientation and placement of CMUT array in k-wave simulation space.

After determining the grid sizes, whole simulation space and medium is constructed. Another consideration for having appropriate simulation durations is deciding on the size of the transmission medium in three dimensional space. This size is determined by considering the location of sensors.

In order to have an accurate simulation sensors have to be placed radially around the transducer. By this way, each sensors position will represent the radial radiation data of the transducer. Thus, maximum number of sensors that can fit around the transducer is placed, which corresponds to 81 sensor elements consisting of one voxel in k-wave space. Hence, each sensor element has equal distance to the center of the transducer, which is determined by a specific radius. This distance (radius) is determined by considering the Rayleigh distance of the transducer and also the simulation duration.

Since this simulation space is also intended to be used in beamforming simulations, sensors should be placed within the beamformable region, which is the near field of the CMUT array. Hence, the radius should be less than the Rayleigh distance. While selecting the number of voxels that is forming the radius, it is chosen according to the multiples of two. The Rayleigh distance is equal of 1406 voxels. Hence, firstly 1024 voxels are used for a simulation;

however, the elapsed time for the simulation was longer than 4 days, which is not convenient for practical simulation. Thus, the number of voxels decreased down to 512, which is equal to 16.384 mm. With these dimensions the simulation is ended in 81 hours, which is a fairly acceptable duration with appropriate distance to the center of the transducer.

In order to prevent scattering from the so called walls of the simulation space, perfectly matched layer (PML) is used. By this way acoustical wave propagation in an infinite space is imitated. Hence, 10 voxels from each plane is used as PML, leaving the total propagation medium with the dimensions of 15.744×32.128×3.456 mm (492×1004×108 voxels), where it is indicated as X×Y×Z axes. Due to radial symmetry the Y dimension is twice of X dimension and also due to the symmetry of the transducer, azimuth and elevation plane transmission will be equal. Thus, the simulation duration is decreased by using this symmetry and decreasing the dimension on the Z axis.

Finally, the medium is determined according to the properties of water. Attenuation, nonlinearity coefficient, density and speed of sound parameters are inputted according to water material as described in k-wave documentation.

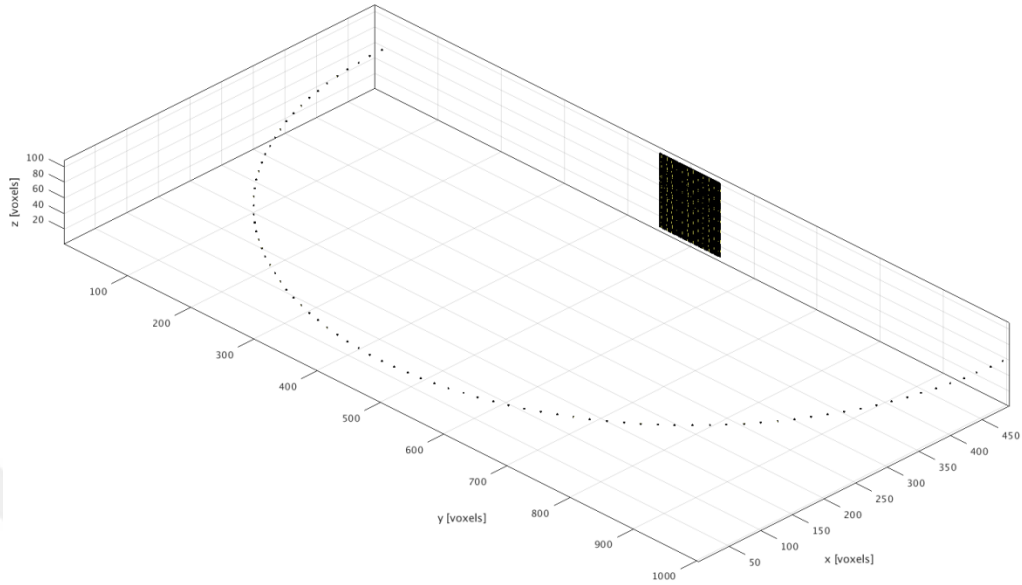


Figure 3.48: Simulation space constructed in k-wave with 32 μm grid (voxel) size and transmission medium dimensions of 15.744 $\times$ 32.128 $\times$ 3.456 mm. Transducer is placed at $x=0$ and the sensors are placed radially with a radius of 15.744 mm.

After constructing the simulation acoustic field in k-wave toolbox, transmitting ultrasonic sources are described. In k-wave two options are available for defining and modelling a pressure source, which are monopole and dipole sources. Since dipole sources are exerting force on the surrounding medium and moves it, physical displacement of the CMUT membrane can also be modelled as dipole source [45].

As explained earlier, one CMUT element is specified by using 25 voxels in k-wave space in order to have equivalent spacing and placement of the elements in the array. However, due to having multiple sources in order to maintain one CMUT, pressure outputs of the dipole sources in k-wave have to be adjusted. This adjustment is done linearly by considering the area of the voxels.

Finally, after carrying out the orientation and pressure amplitude compensation of these sources, time domain inputs have to be designated. In order to have the maximum accuracy in this simulation, time domain analysis

results gathered from ADS are fed into k-wave toolbox. By matching up each output channel of the ADS time domain analysis result to the channels designated in k-wave space, a three dimensional acoustic field simulation is constructed. All of the time domain input signals obtained by ADS is the 1 cycle 75 volt PWM signals that is also presented in Section 3.6 Pulse Width Modulation (PWM)

According to these specifications, designated transducer voxels are used for transmission through homogenous water medium. Eighty one sensors that are facing this transducer with an equal distance to its center are used for time domain reception. By using 1 ns second time step sizes total of 32 μ s long simulation is completed. In order to use 1 ns time step, source input values gathered from ADS is interpolated correspondingly. After recording each time domain signal received from each sensor, maximum pressure amplitudes of these signals are used to indicate the value for each angle data of the radiation pattern.

In order to have a fair comparison, pressure output obtained by ADS is used for beamforming in MATLAB. Manually beamforming is done for 81 angle points (where the sensors are located in k-wave simulation space) by using (3.6) and similarly maximum of the resulted time domain data is used to form the computational radiation pattern by using MATLAB.

It is realized that having uniform pressure distribution on the voxels in k-wave results in a radiation pattern similar to piston membrane. Thus, clamped membrane deflection distribution is applied on each CMUT element constructed with 5×5 voxels. Both piston membrane and clamped membrane radiation pattern is shown in the following figure.

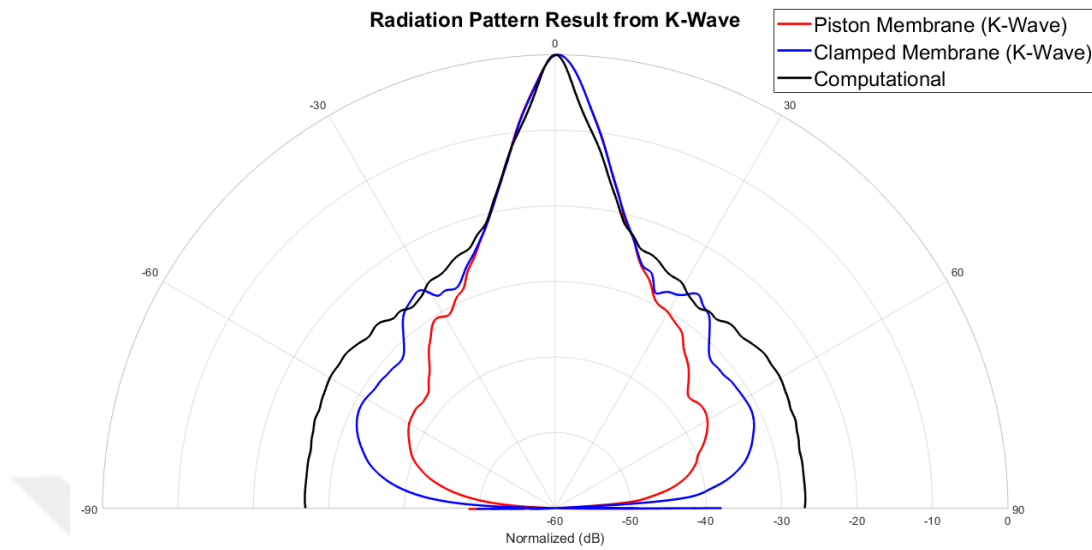


Figure 3.49: Radiation pattern simulation result obtained by k-wave and computational radiation pattern is shown.

3.8 Beamforming Simulations

Same approach that used in Section 3.7 Radiation Pattern Simulations, is applied for demonstrating the beamforming capabilities of the designed transducer that operates at 7.5 MHz. As the sensors are placed with a half circle orientation with same distance, radius to the center of the transducer, transmit beamforming delays are calculated for different focus angles on the elevation plane. Focusing on a 3-D space in front of transducer is possible however, by using the symmetry of the array elements' placement; results that will be obtained for elevation plane will be same for azimuth plane.

Before executing transmit beamforming in k-wave, firstly the validation of the delay values is done. Since, the designed transducer will not be driven in a traditional way, the verification of whether the conventional beamforming time delay calculation is applicable also for unbiased mode of operation. Since mutual impedance radiation is a very dominant feature in the operation of CMUTs, during the beamformed transmission the mutual radiation impedance will affect the waveform that will be transmitted. Thus, both the effect of mutual

radiation impedance and unbiased mode of operation is investigated by cross-correlating the time domain pressure outputs gathered by ADS.

For this purpose, delay values for 30° steering angle are calculated in MATLAB at elevation plane for symmetry. Calculated delay values are used as the input value of delay parameter defined in ADS for the PWM voltage sources. After gathering the time domain pressure waveforms of the steered transmission, each CMUT element is cross-correlated with the consecutive element in order to identify the actual lag between each transmission through a single element. Lag values identifies the steered angle since one pressure source can be designated by its consecutive element in a line array configuration [37].

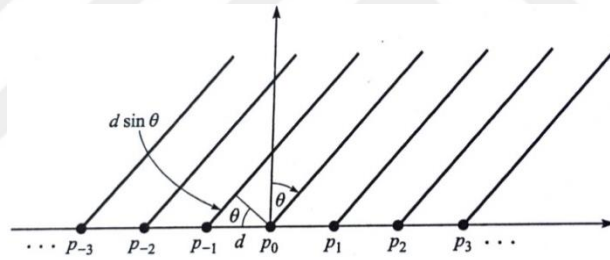
$$p_{-1} = \frac{A}{r} e^{j[\omega t - k(r + d \sin \theta)]} = p_0 e^{-j2\varphi} \quad (3.5)$$


Figure 3.50: N point source demonstration for (3.5) [37].

After determining these lag values, the input delay values are compared. Since cross-correlation operation is done in a line array configuration similar to Figure 3.50, each row is compared with the input delays. Although only several and distinguishing rows are shown in Figure 3.51 each comparison results in very similar difference values. In order to have more detailed comparison, output waveforms gathered from ADS is interpolated to obtain 1ns of time step for transient analysis results. According to the comparison, maximum deviation between the cross-correlation lag values and transmit beamform input delay is 2ns, which is smaller than the step resolution of the ultrasound measurement system, DiPhAS. Thus, it is concluded that the conventional transmit

beamforming delay calculation is also applicable for unbiased mode of operation for CMUTs.

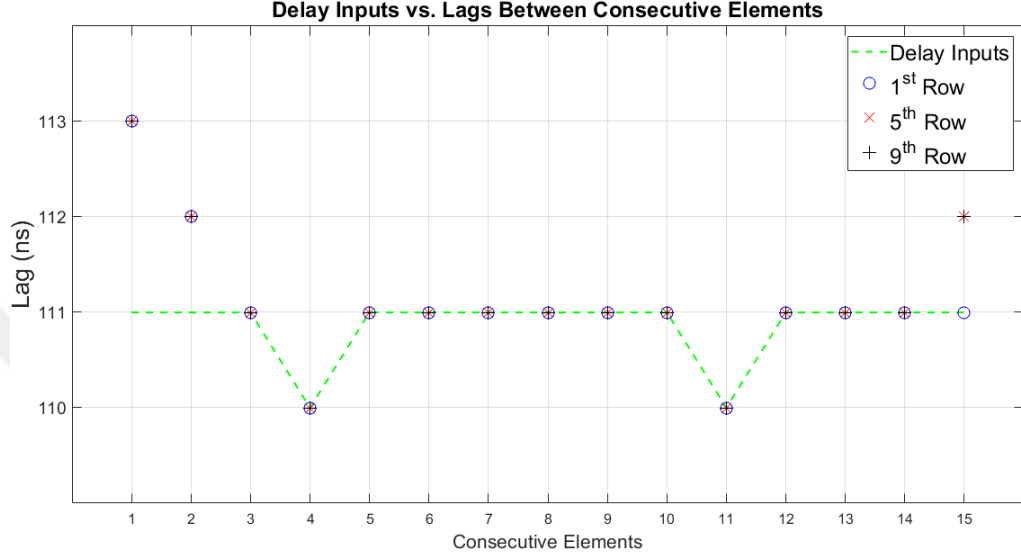


Figure 3.51: Input delays calculated by MATLAB is compared with the lag values obtained by the cross-correlation results of two consecutive CMUT elements' time domain pressure outputs driven with 1 cycle PWM signal in ADS in a row of the phased array.

After validating the beamforming time delays for unbiased mode of operation, focusing on a single point by using 256 elements of the phased array as a function of angle is executed. For each channel and focus point, time delays are calculated using [46],

$$\tau_n = \frac{\left[r - \sqrt{(x_r - x_n)^2 + z_r^2} \right]}{c_0} + t_0 \quad (3.6)$$

where r is the distance from origin to the focal point, which the radius of the half circle that the receive sensors are placed, x_n is the distance from origin to the center of an element and t_0 is the fictitious value in order to avoid negative or unnecessary large delay values. Angle of the focussed point is selected only on the elevation plane in order to avoid the computation is azimuth plane. Hence, focus points' position is equal to the sensor position located at the corresponding angle to the normal of the center of the transducer.

By this way, comparison in terms of pressure received by the sensors at the focused angle and other sensors is done. Radiation pattern is shown in order to compare the plane wave transmission and focused transmission to specific angles normal to the center of the transducer.

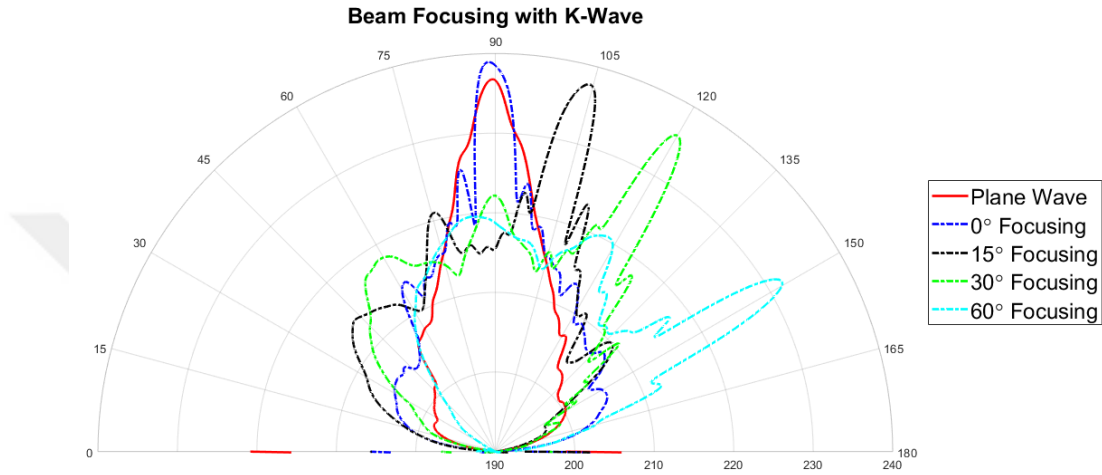


Figure 3.52: Plane wave transmission compared to beamformed transmission with different focusing angles. R-plane is shown in dB re. 1 μ Pa.

As the angle degree of focus increases it is observed that the peak pressure at the focus point is decreasing. This phenomenon is due to the diffraction limited focus [47]. As the degree increases focusable point area increases, thus the total energy distributed to unit area decreases.

After obtaining the radiation pattern results for focused transmissions, time domain waveforms received by the relevant sensors is observed. Since focusing is directly applied to the position of the sensor, received time domain signals are compared on the relative angle of the position of the sensor normal to the center of the transducer. Thus, for the transmission with focusing on 0°, 41st sensor's received signals for each transmission (plane wave, 0°, 15°, 30° and 60° focused transmission) is compared. Similarly, for 15°, 30° and 60° focused transmissions, 47th, 53rd and 59th sensors shown in Figure 3.48, is used respectively. Within these comparisons, side lobe levels and Rayleigh-Bloch wave peak pressure

difference levels are obtained. All values are compared according to the maximum peak pressure obtained by the respective sensor.

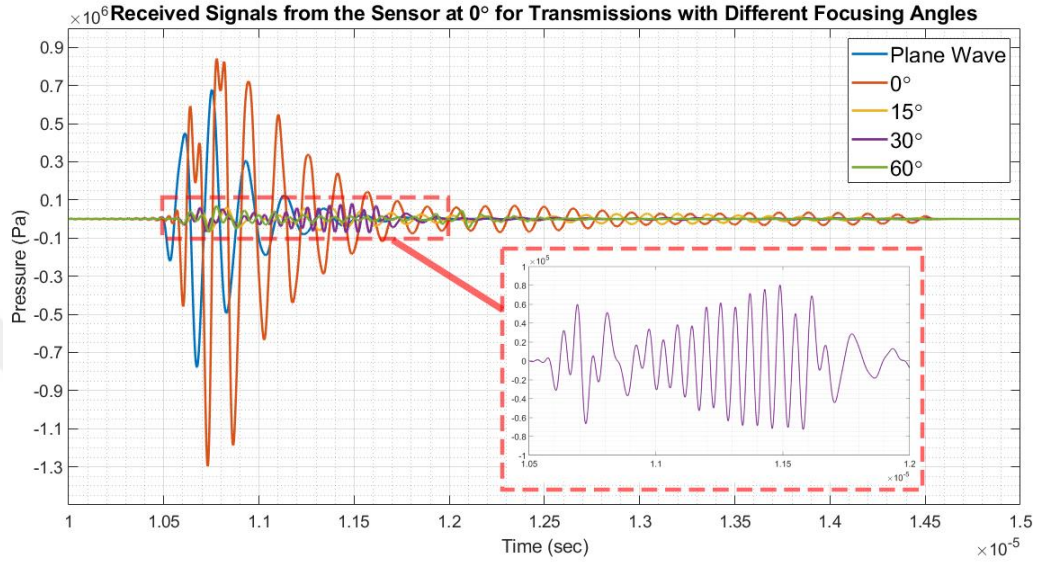


Figure 3.53: Received signals from the sensor at 0° (41st sensor) located on the k-wave simulation space, for different transmissions. Side lobe level is calculated to be -25.93 dB and Rayleigh-Bloch wave peak pressure difference to be -33.39 dB.

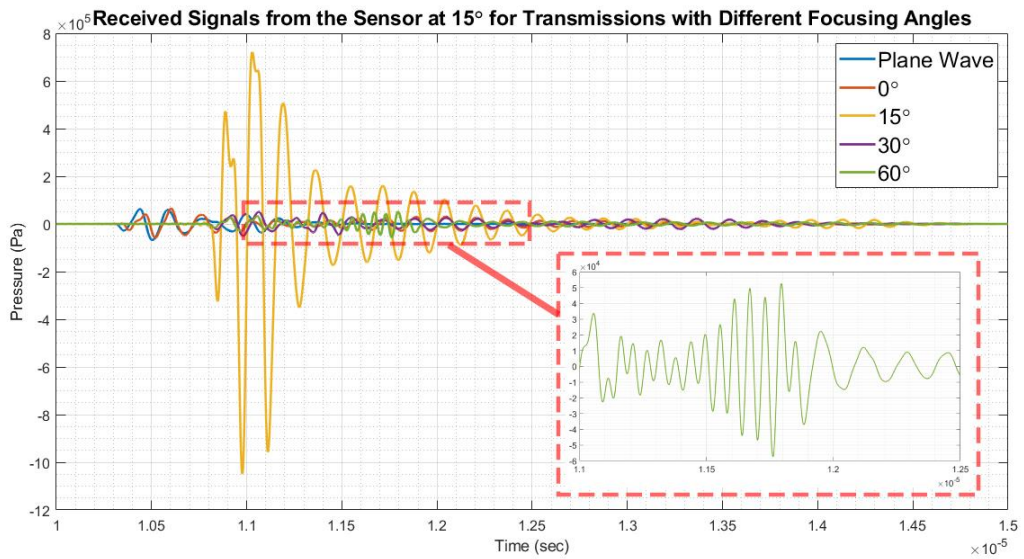


Figure 3.54: Received signals from the sensor at 15° (47th sensor) located on the k-wave simulation space, for different transmissions. Side lobe level is

calculated to be -25.28 dB and Rayleigh-Bloch wave peak pressure difference to be -33.67 dB.

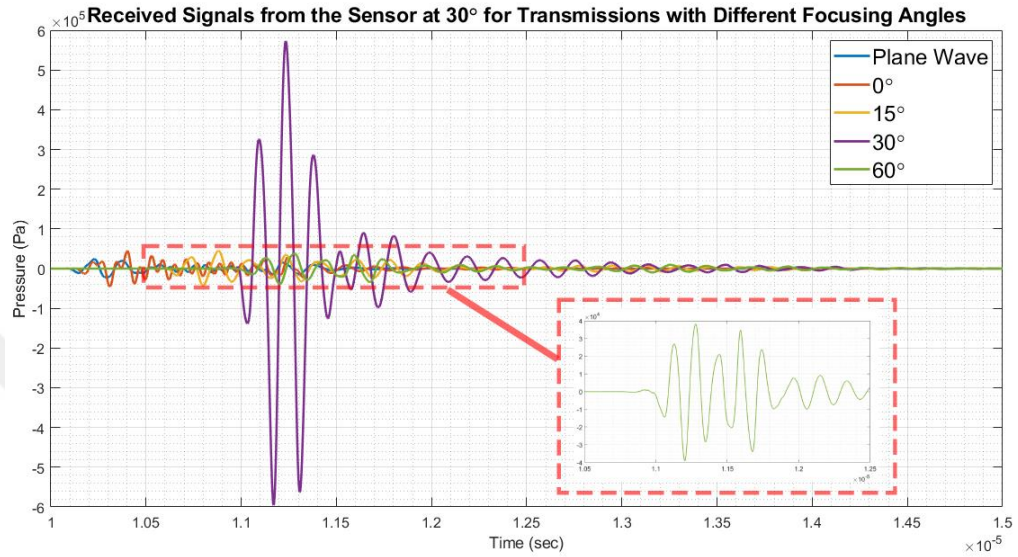


Figure 3.55: Received signals from the sensor at 30° (53rd sensor) located on the k-wave simulation space, for different transmissions. Side lobe level is calculated to be -23.85 dB and Rayleigh-Bloch wave peak pressure difference to be -33.83 dB.

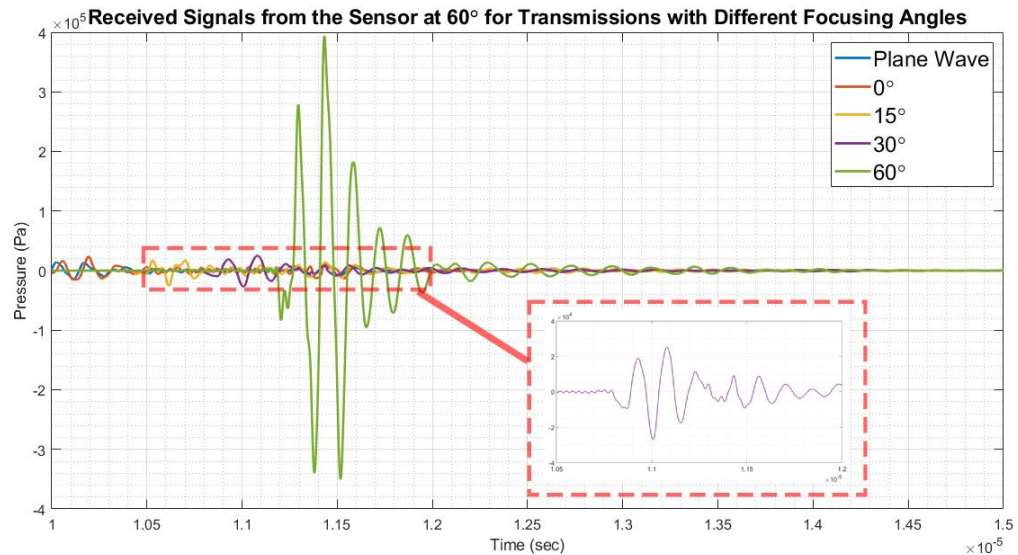


Figure 3.56: Received signals from the sensor at 0° (59th sensor) located on the k-wave simulation space, for different transmissions. Side lobe level is

calculated to be -23.33 dB and Rayleigh-Bloch wave peak pressure difference to be -32.21 dB.

3.9 Pressure Field Pattern

After observing that the focusing is applicable for this mode of operation, field patterns for different transmission schemes are also investigated. As explained earlier, as the focused point's angle is increased according to the normal of the transducer surface, maximum received signal is decreased because of the phenomenon of diffraction limited focusing. In order to investigate this phenomenon, field patterns are also become a beneficial tool.

Simulations are done again in MATLAB toolbox, k-wave. Similar simulation space construction is used in field pattern simulations. While the grid sizes, transducer orientation and placement and propagation medium dimensions are kept the same, circularly placed sensors are not used in this simulation. Instead, the sensors are placed all over the x-y plane, which results in total of 493968 (492×1004) sensor voxels. Each of these sensors is recording the received pressure signals in time domain. By using the maximum peak points of these received signals, value of each sensor on the plane is determined. After calculating each value for each sensor, data is normalized over the whole sensor plane. By this way the final field pattern image is constructed.

Firstly, plane wave transmission (zero delay) is done with the pressure output signals gathered by ADS is used as the input signal of the transducer placed in k-wave. Both the main lobe and the side lobes can be observed from the resulted field patterns. At the corners of field patterns there are some regions, which shown by very low pressure. However, due to the transient simulation principle of k-wave, it means that the input signal could not reach to that point of the simulation domain, which can be ignored or the field pattern at these points can be simulated by increasing the simulation time parameter in k-wave.

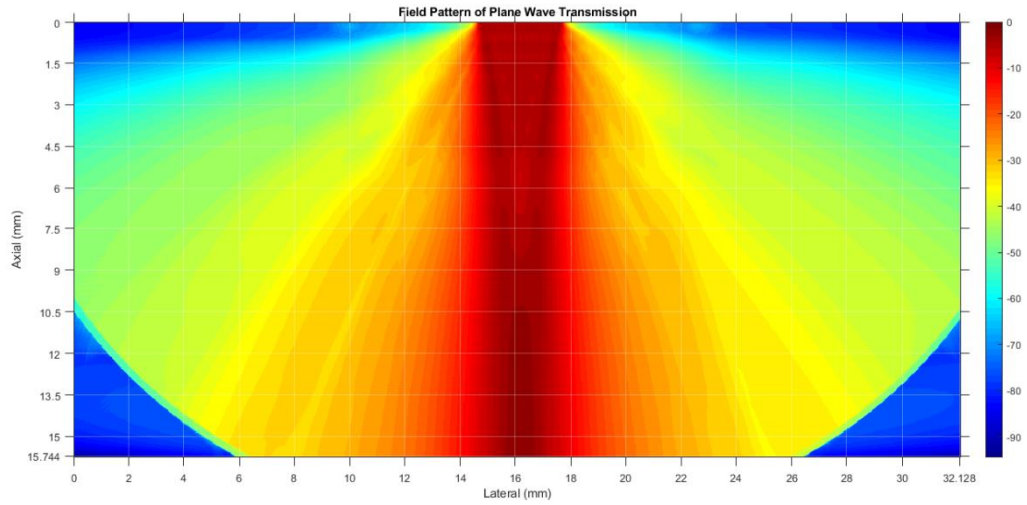


Figure 3.57: Field pattern resulted by plane wave transmission (zero delay) in k-wave at 7.5 MHz.

Similarly, for 0° focused transmission the same pressure outputs gathered by ADS used in Figure 3.53 also drive the transducer for constructing the field pattern. Focusing is done at 0° degree to the normal of the transducer surface and 15.744 mm away from the transducer on the x-y plane (center of the transducer surface). Again because of the symmetry of the transducer only elevation plane is considered.

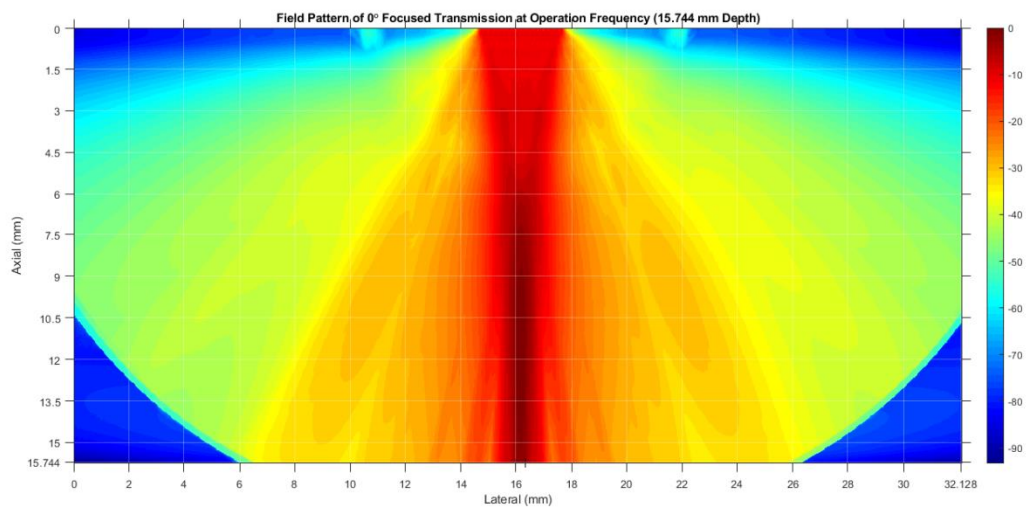


Figure 3.58: Field pattern resulted by 0° focused transmission in k-wave at 7.5 MHz and 15.744 mm distance to the center of the transducer surface.

0° focused transmission is repeated again by changing the focused depth. Focusing depth is halved to 7.872 mm, and pressure outputs are gathered from ADS accordingly.

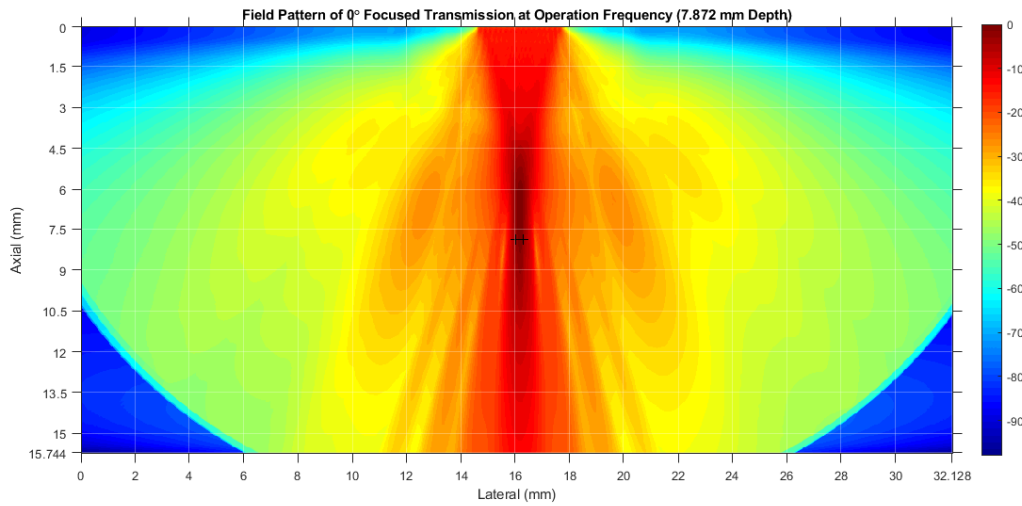


Figure 3.59: Field pattern resulted by 0° focused transmission in k-wave at 7.5 MHz and 7.872 mm distance to the center of the transducer surface.

Same specifications for focusing depth and angle are used again by only changing the input signals' frequency. The transient pressure simulation in ADS is repeated by using the half of the peak frequency as the electrical input frequency. As a result, acoustical output signal at 6.36 MHz, which is determined earlier as the peak frequency, is used as the input signal for the transducer constructed in k-wave simulation domain. With this simulation it is observed that beamforming is also applicable at the peak frequency and this mode of operation.

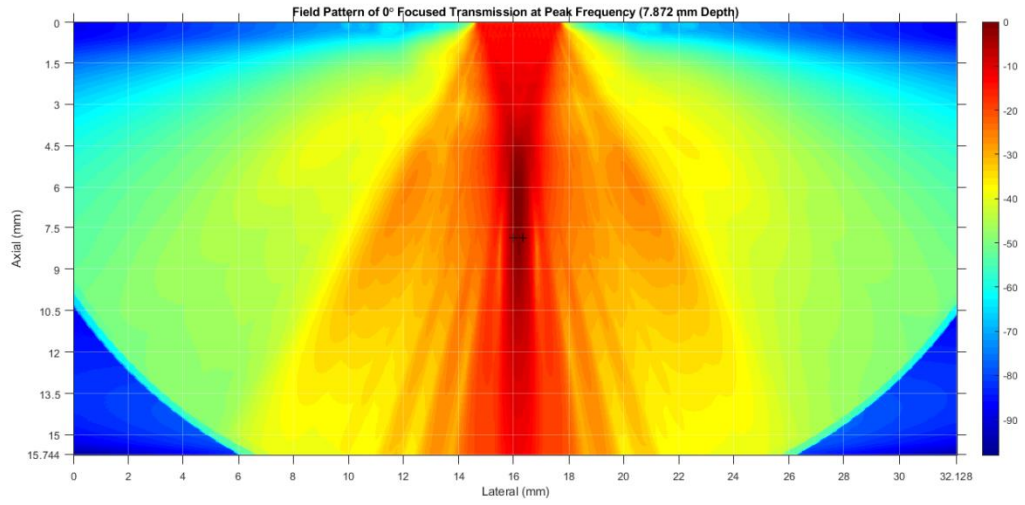


Figure 3.60: Field pattern resulted by 0° focused transmission in k-wave at peak frequency, 6.36 MHz and 7.872 mm distance to the center of the transducer surface.

Similar simulation used in Figure 3.55, also drive the transducer for constructing the field pattern for 30° focused transmission. Focusing is done at 30° degree to the normal of the transducer surface and 15.744 mm away from the transducer center on the x-y plane (center of the transducer surface).

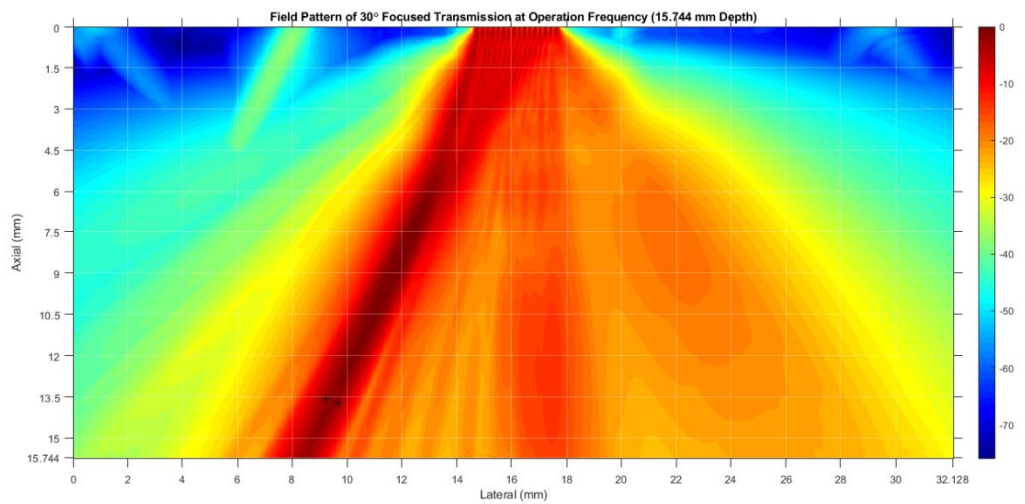


Figure 3.61: Field pattern resulted by 30° focused transmission in k-wave at 7.5 MHz and 15.744 mm distance to the center of the transducer surface.

Finally, for comparison reasons, field pattern of 0° focused transmission at 7.872 mm is repeated with DC biased electrical input signal at 7.5 MHz. Value of DC bias is chosen according to the median deflection of the membrane during unbiased mode of operation (52.5 V_{DC}) and AC voltage level is designated in order to have the same output power with unbiased mode of operation (28.8 V_{ac}).

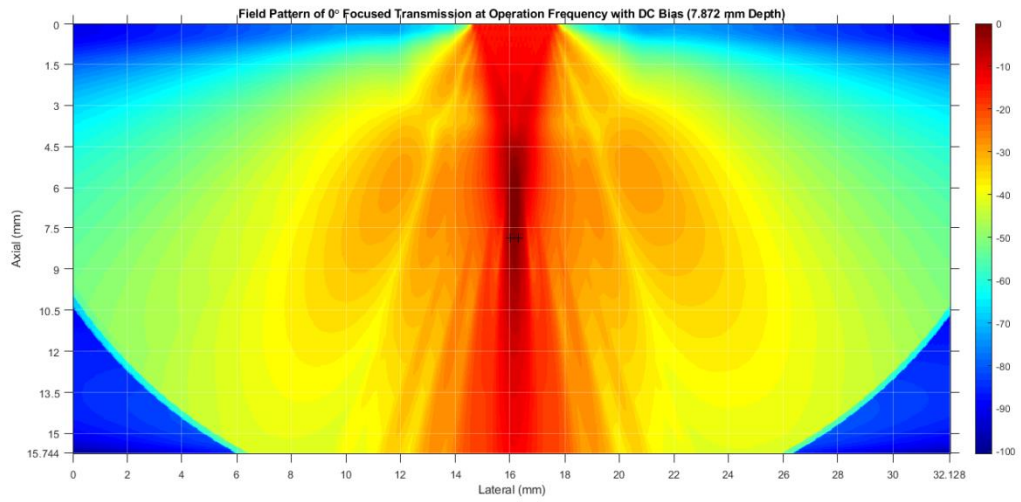


Figure 3.62: Field pattern resulted by 0° focused transmission in k-wave at 7.5 MHz and 7.872 mm distance to the center of the transducer surface with biased mode of operation.

After constructing field patterns for different transmission schemes, frequency, focusing angle and depth, diffraction limited focusing is investigated. For this purpose, physical points (x-y coordinates) where the received signal is -3 dB of the normalized total received pressure field pattern over the propagation medium, are determined. Intrinsically, two x-y coordinates are obtained and the distance between these coordinates specifies the quality and resolution of the beamforming. This distance is denoted as 3-dB definition, $d_r(3\text{ dB})$, where the diameter of the beam at the 3-dB points [48]. In Figure 3.58, Figure 3.59, Figure 3.60 and Figure 3.61, these coordinates are marked with plus signs at the focused depth. According to the specified markings, distances between these coordinates are calculated and shown in Table 3.2.

Table 3.2: $d_r(3 \text{ dB})$ in terms of wavelength is shown for different drive frequencies, focus angles and depths. λ is the wavelength of the operation frequency of 7.5 MHz and λ_p is the wavelength of the peak frequency, 6.36 MHz.

Acoustical Output Frequency	Focus Angle	Focus Depth (mm)	$d_r(3 \text{ dB})$
7.5 MHz	30°	15.744	2.53λ
7.5 MHz	0°	15.744	1.76λ
7.5 MHz	0°	7.872	1.69λ
7.5 MHz (DC Biased)	0°	7.872	2.01λ
6.36 MHz (Peak)	0°	7.872	$1.52\lambda_p$

3.10 Power and Intensity

Another important characterization for the designed transducer is done by examining the mechanical power and intensity of the output pressures resulted by ADS. By using the results of harmonic balance analysis with ADS, both mechanical power can be obtained by using (3.7) [37].

$$W_{mech} = \text{real}(f \cdot u^*) \quad (3.7)$$

where f is the force resulted by the transducer and u^* is the complex conjugate of the particle velocity of the membrane. The mechanical power implies the radiated power to the medium from the transducer. Thus, generated power from individual CMUT elements can be superposed to find the total radiated power from the transducer.

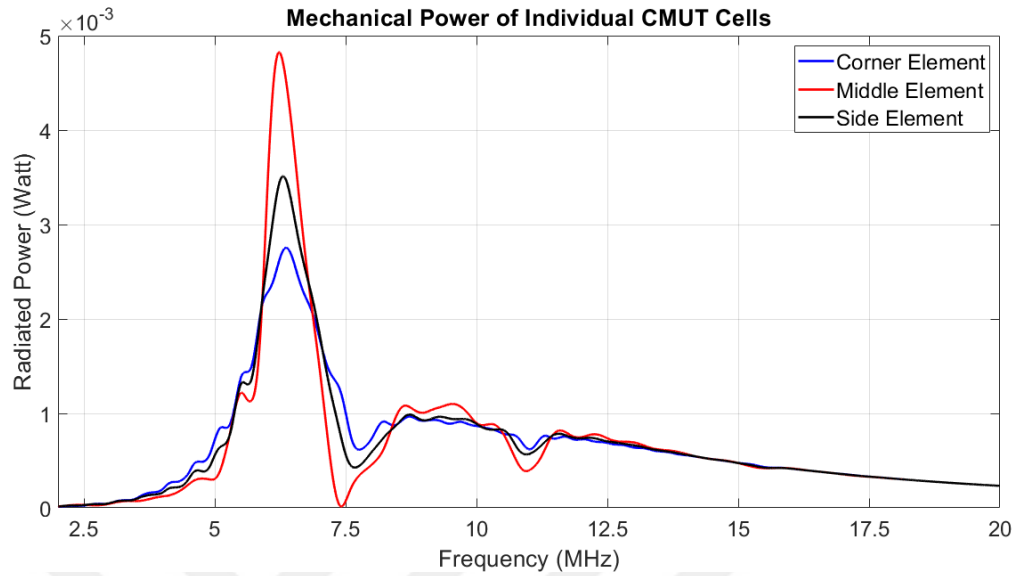


Figure 3.63: Second harmonic of the harmonic balance analysis is shown for mechanical power for individual CMUT cells. Radiated power at 7.5 MHz is found for corner, middle and side CMUT elements as 0.997×10^{-3} , 0.777×10^{-3} , and 0.557×10^{-3} Watt respectively.

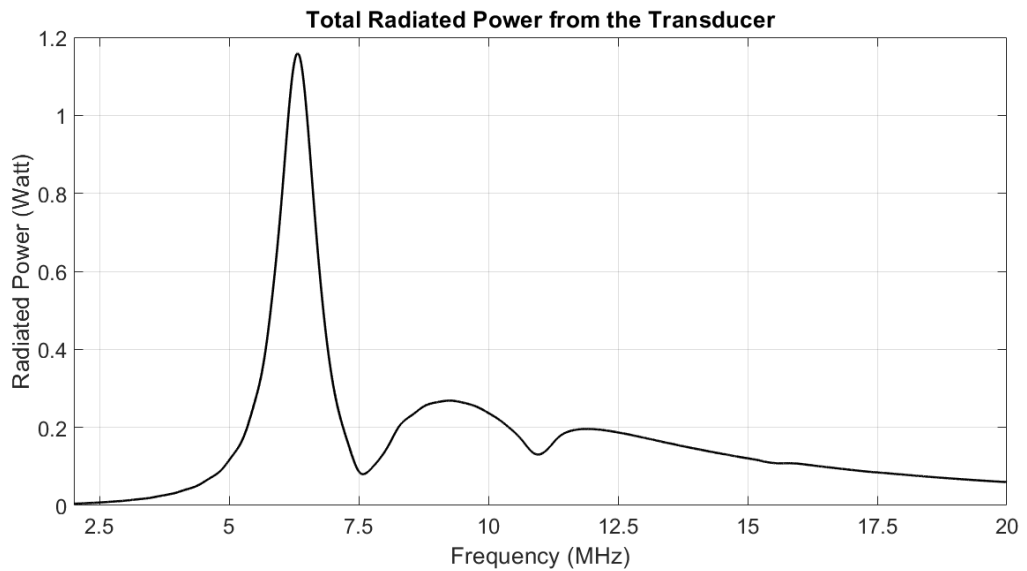


Figure 3.64: Second harmonic of the harmonic balance analysis is shown for mechanical power for the transducer by superimposing every CMUT element in the transducer array. Total radiated power for the transducer is found to be 86.6 mW.

Similarly to the harmonic balance analysis for pressure outputs in Figure 3.3, at peak frequency higher power output can be obtained as 1.159 Watt. However, for pressure output at 7.5 MHz operation frequency, pressure difference is very much similar in individual CMUT cells, though for power output results, middle element and corner element power difference is in order of 10^3 . Thus, for each individual CMUT element peak radiated power values are shown as heat map in order to show the regions where the most radiation occurs.

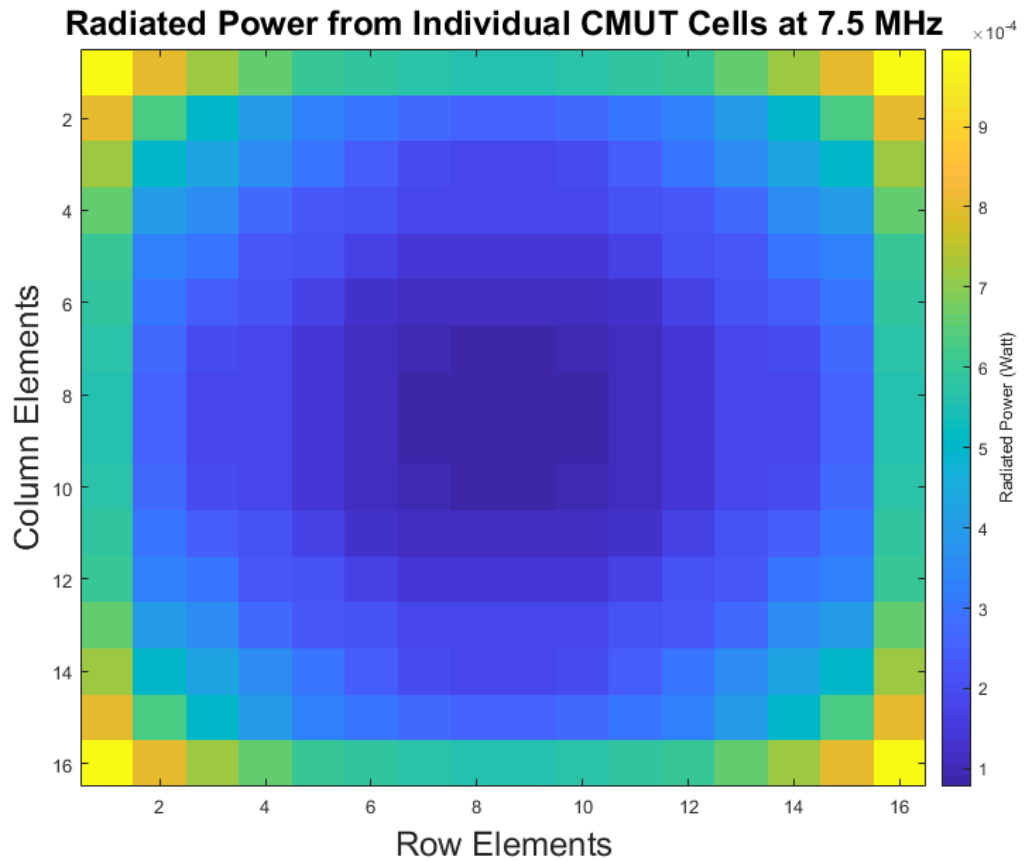


Figure 3.65: Heat map of radiated power from individual CMUT cells of the 16×16 phased array at the operation frequency of 7.5 MHz.

Similar heat map is obtained at the peak frequency of 6.36 MHz, where the maximum radiated power regions are different from the radiation pattern at the operation frequency.

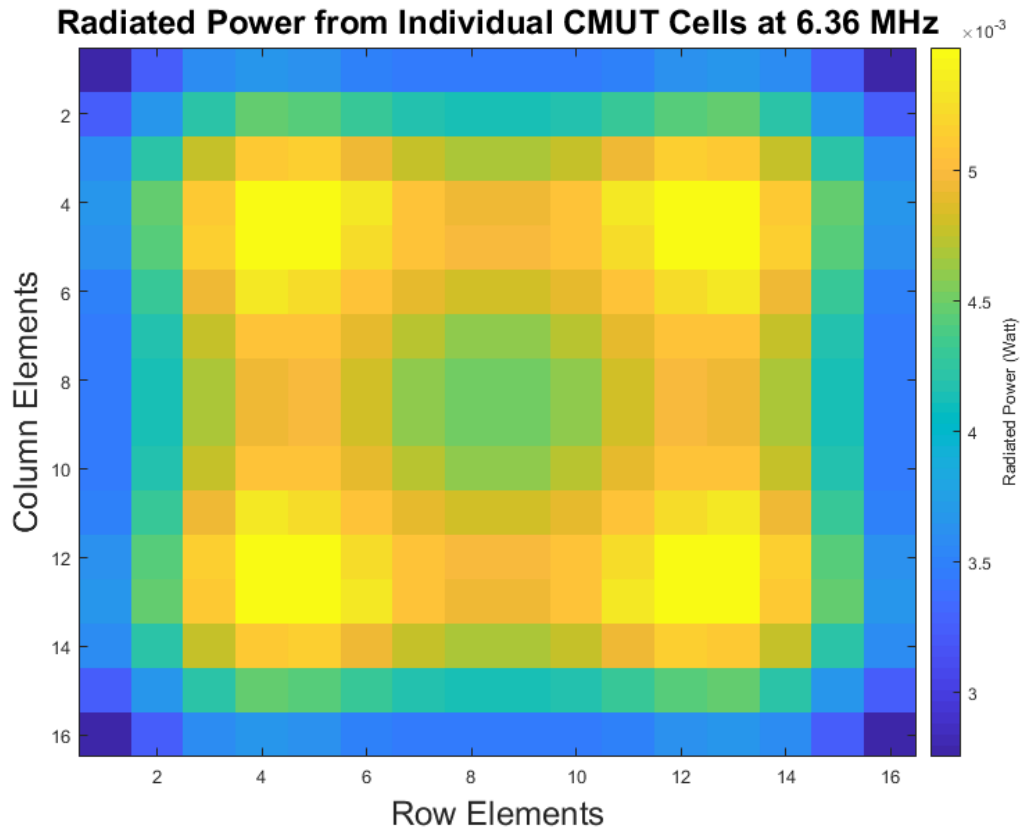


Figure 3.66: Heat map of radiated power from individual CMUT cells of the 16×16 phased array at the peak frequency of 6.36 MHz.

In Figure 3.63 and Figure 3.64, only second harmonic power values are shown. In unbiased mode of operation fundamental and odd harmonics are non-existent. Even harmonics of the electrical drive frequency is dominant in this mode of operation. Most dominant factor in this mode of operation is the second harmonic of the electrical drive frequency since the other even harmonics are decaying with order of 10^3 and can be neglected.

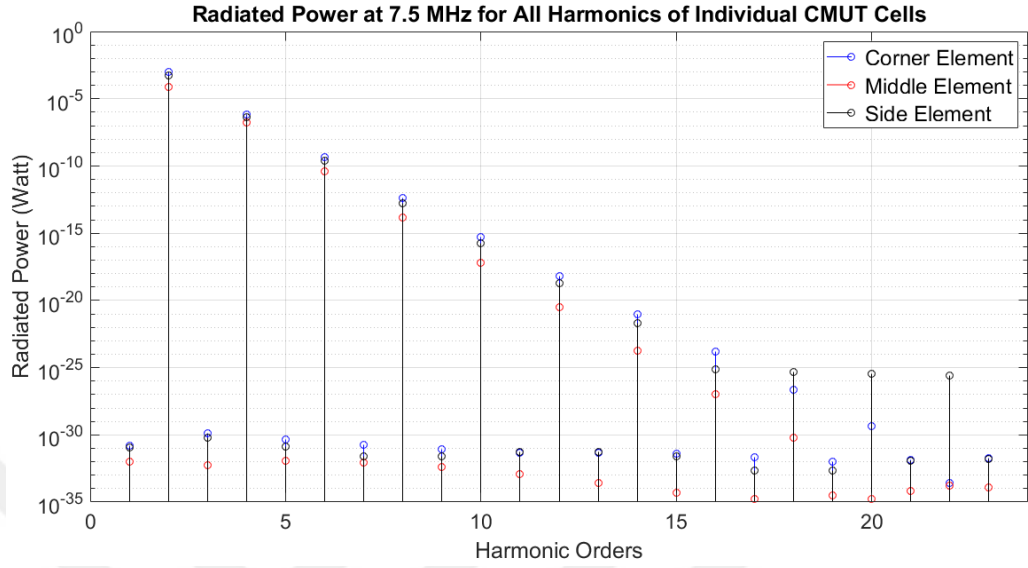


Figure 3.67: Every harmonic data resulted from harmonic balance analysis for radiated power is shown. Odd harmonics of the fundamental of the electrical drive frequency is at a level of 10^{-30} , which can be interpreted as numerical error; hence it is equal to zero. For even harmonics, radiated power decays linearly with a rate of 10^{-3} until 18th harmonic and then stays at same level.

In order to obtain more accurate results, time domain analysis data is used in order to include higher even harmonics and also in order to calculate the intensity resulted by the transducer. As indicated in (3.7), mechanical power or radiated power is found by using the real part of the multiplication of force with conjugate of the particle velocity. However, intensity must include both real and imaginary parts of pressure and particle velocity multiplication. Thus, (3.8) is used for calculating the intensity of the phased array transducer.

$$I = \left[\sum_{i=1}^{256} \left(\frac{1}{t_{av}} \int_{t_{av}} |f_i \times u_i^*| dt \right) \right] / S \quad (3.8)$$

where, i is the number of CMUT elements in the array, S is the total area of the 16×16 phased array transducer, f is denoted as the force of each CMUT element and u^* is the complex conjugate of the particle velocity of the individual CMUT elements.

Time domain analysis shown in earlier sections are used in order to obtain the intensity results for each transmission with different cycles. Total duration of transient analysis is kept the same in order to have a fair comparison as 4 μ s. Power values are obtained by superposing the power outputs of individual CMUT cells and similarly intensity is found by dividing the power summation to transducer surface area.

Table 3.3: Power and intensity values obtained for different transmission schemes and different cycles over the transducer surface.

	75 V _{ac} at 7.5 MHz		MVM		Peak (6.36 MHz with 75 V _{ac})	
	Power (W)	Intensity (W/cm ²)	Power (W)	Intensity (W/cm ²)	Power (W)	Intensity (W/cm ²)
Sinusoidal 0.5 Cycle	0.0055	0.1113	0.2984	5.8994	0.0051	0.1035
Sinusoidal 1 Cycle	0.0140	0.2952	0.3768	7.5010	0.0160	0.3422
Sinusoidal 4 Cycle	0.0250	0.5567	0.4739	9.7263	0.1316	2.8879
Gaussian Enveloped Tone Burst	0.0146	0.3032	0.5856	10.8678	0.0602	1.2263
PWM 0.5 Cycle	0.0085	0.1698	0.3000	5.5937	0.0075	0.1451
PWM 1 Cycle	0.0213	0.4472	0.3947	7.3303	0.0236	0.4825
PWM 4 Cycle	0.0390	0.7743	0.5201	9.0862	0.1847	3.9295

Chapter 4

Fabrication

4.1 Mask Design

Since there are two different designs, mask designs completed for both resonance frequencies of 7.5 MHz and 18.5 MHz. In addition, masks are designed accordingly to the determined process flow. After determining the process flow, some limitations were taken into account, such as the ability to fabricate minimum width of three μm wires.

Firstly, the distribution and fanning out of the wires that are connecting CMUTs and electrical pads are designed. In order to ease the integration process of CMUT chip and PCB, the electrical pads are determined to be 0.5x0.5 mm, which is an applicable dimension for using shadow masks instead of chrome masks, which are typically more inexpensive. However, this brings the disadvantage of using less area of the wafer. Thus, an optimum placement of these electrical pads is needed to be designated.

After placing the electrical pads in an area efficient manner, fanning out of the wires designed. Since the CMUTs are designed as 16x16 elements in a square manner, connection of the inner cells of the array should be fanned out. While fanning out firstly the number of spacing between two consecutive outer cells of the array and the number of inner cells are determined. With a trivial calculation, sixty spacing should be used in order to reach hundred and ninety-six cells. In order to have an equal distribution with minimum wires in one spacing, it is calculated that sixteen spacing should be used for reaching four cells while other forty four spacing using three wires. On the other hand, on our cleanroom facility, there is an approximate limitation for fabricating minimum wire width of three μm . Thus, while using the spacing between two consecutive outer cells of the array, the minimum separation width should be 27 μm .

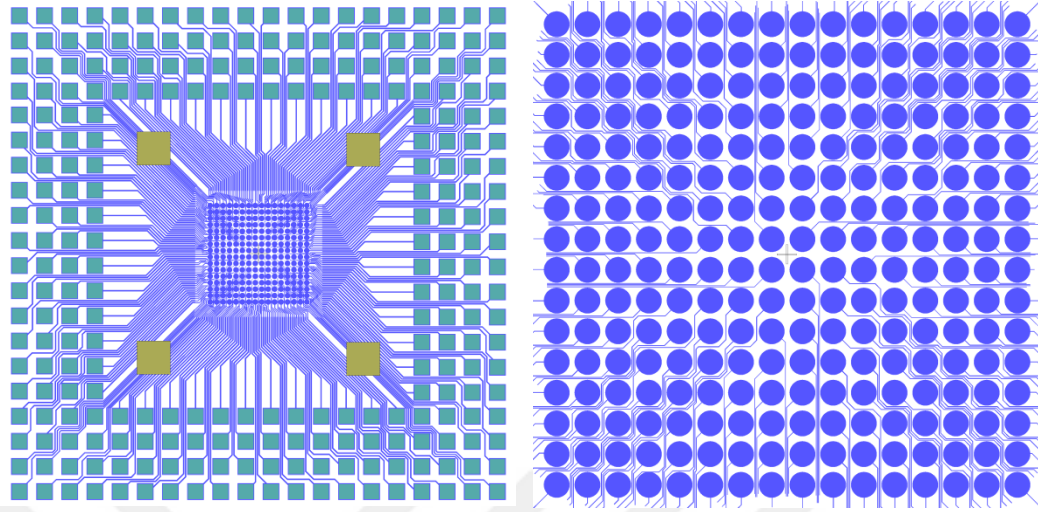


Figure 4.1: Full device mask design of 7.5 MHz (left) and the 16x16 CMUT array mask design (right).

However, according to the design procedure described in section 2.4, pitch for 18.5 MHz array is determined as $77.8\text{ }\mu\text{m}$, which leaves spacing of $13\text{ }\mu\text{m}$ between two consecutive cells. In order to meet the design specifications by considering the fabrication limitations, 256-element design is modified by removing the middle elements of the array. With the expense of lower acoustical output power, new design consist 180 elements while preserving the 16x16-array structure. By this way two wires are fanning out from the spacing between two cells by pushing the limits of wire width to $2.6\text{ }\mu\text{m}$. On the other hand, with the capability of fabricating one μm width of wires, 256-element design can also be manufactured similarly to the 7.5 MHz design.

Then according to these specifications, appropriate fanning out design is determined and then applied to both masks for different resonance frequencies.

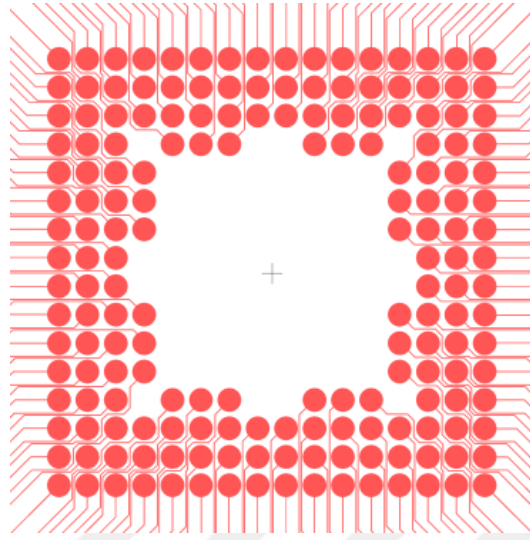


Figure 4.2: 180-element mask design for 18.5 MHz resonance frequency array.

Another consideration was the DC resistance of the wires. Because of the closely packed structure of the array, fanning out of the wires that are connected to the bottom electrodes of the CMUTs results in relatively long wires. The longest wire in the 7.5 MHz array is determined to be 2.08 mm with a width of four μm . According to these values, the largest resistance of a wire that is connected to an inner cell of the array and reaches till the electrical connection pads, is calculated as $39.61 \, \Omega$ when the thickness of the gold is selected as 500 nm. Otherwise, the resistance becomes too large, which will result in high loss and concurrently because of the heat dissipation, the wires can be damaged during the operation.

In this work only the design with 7.5 MHz resonance frequency is chosen to be fabricated because of the time and resource limitations.

4.2 MEMS Process Flow

4.2.1 Cavity

Firstly, proper cleaning of the wafers maintained with acetone, isopropanol and distilled water. After cleaning the wafer, 35 nm of chrome is deposited with e-beam evaporator on the wafer for creating the hard mask. This hard mask is

very crucial since in further processes; platinum will be deposited, which needs to be conducted in very high temperature because of the high melting point of the platinum. Unless this chrome layer is present, only the photoresist mask does not withstand this high temperature and starts to bend and corrupt [49].

After depositing chrome lithography is done with using Microchemicals AZ4562 positive photoresist (Ulm, Germany). This photoresist is spin-coated over chrome with 6000 rpm which approximately results in 5 μm . This value is determined according to the ratio between the smallest features in the mask design, which is 3 μm . After spin-coating, UV exposure is done by using the chrome mask shown in Figure 4.1. After few trials, optimum exposure power is found as 50 mJ/cm^2 . Also because of the small feature sizes (3 μm) vacuum and hard contact exposure with constant dose is applied by EVG 620 mask aligner system (St. Florian, Austria). Upon completing the UV exposure development is done by using Microchemicals AZ400K and the development process is completed around 8 minutes.

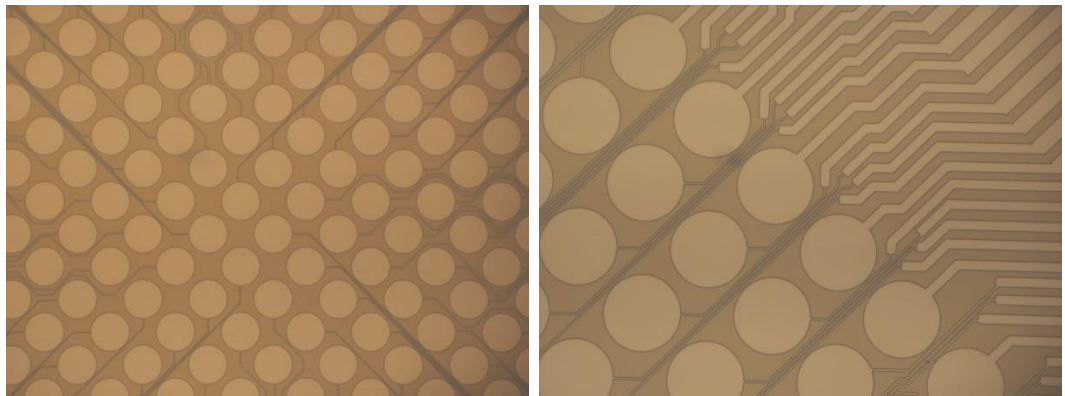


Figure 4.3: Microscope image after lithography process is done.

Next step after lithography is to etch the chrome areas from the regions where the cavity will be formed for the bottom electrodes. For this process inductively coupled plasma (ICP) with Argon plasma is used for anisotropic etching of the chrome. Spacing between the thinnest wires is designed as 4 μm thus undercut of photoresist will cause significant difficulties in further processes.

ICP process is done in several cycles. According to our previous experiences the wafer should be faced with air, otherwise successful etching of chrome could not be maintained. Thus, the process is done by seven cycles of argon plasma exposure for one minute and four cycles of exposure for one and a half minute. Between each cycle, vacuum is broke in carousel and nitrogen is flowed on the wafer. After total of eleven cycles, chrome is fully etched.

However, because of the variations in the chrome thicknesses between the wafers, full etching of chrome can be maintained in less cycles of ICP with argon plasma but for certain etching of chrome eleven cycles is applied for each wafer. On the other hand, this additional cycles result in etching of Pyrex. By using a dummy wafer for testing the depth of the cavities, the depth caused by this additional ICP process by argon plasma resulted in approximately 250 nm (including the chrome thickness).

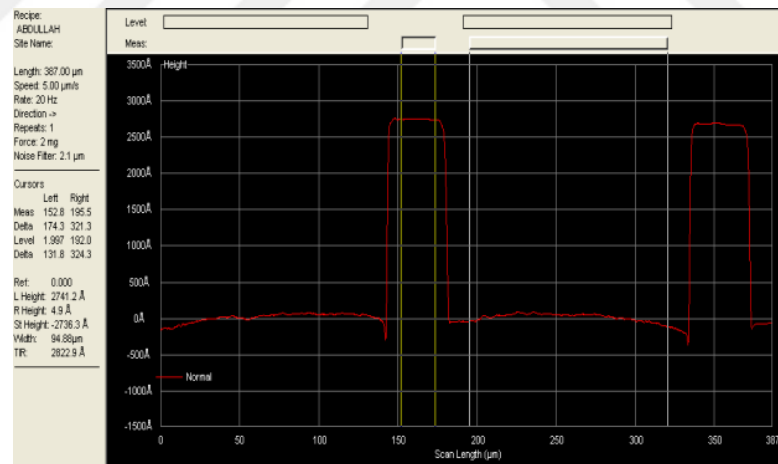


Figure 4.4: Stylus profilometer measurement conducted after eleven cycles of ICP with argon plasma for etching chrome hard mask from the bottom electrode regions. The value shown in the figure is the depth of the etched pyrex with adding the chrome thickness of the hard mask.

As explained in previous section, in order to maintain low DC resistance on the wires, 500 nm of gold is decided to be deposited. Furthermore, adhesion and barrier layers are also needed for successful adhesion of gold. Since chrome is used as hard mask, 100 nm of titanium is used as adhesion layer and also 100

nm of platinum is needed as a barrier layer. Hence, in order to maintain 100 nm of gap height for CMUTs, 800 nm of cavity is needed before the metallization.

From the dummy wafer, it is seen that approximately 250 nm of depth (including the chrome thickness) is maintained. This value is the average value between different devices on the wafer. The minimum value is 220 nm on the middle of the wafer and 270 nm on outer devices. For the remaining 550 nm both anisotropic dry etching (with deep reactive ion etching (DRIE) with ICP by using SF₆ and argon plasma) and isotropic wet etching (with buffered oxide etch (BOE)) is used. However, 480 nm of depth is maintained by dry etching with DRIE. The reason for such procedure is that, 480 nm of etching in BOE can be maintained in approximately 24 minutes; however, because of the isotropic etching figure of BOE, the 4 µm spacing between the wires also gets etched and results in lifting off of the chrome mask and photoresist. Thus, minimum depth with wet etching is maintained. Though, BOE is also necessary in this process flow because after dry etch with DRIE, some residues are formed on the etched areas and in order to clean those residues BOE is used. Furthermore, BOE forms greater undercuts underneath the chrome mask, which is important for easier and more accurate lift-off after the metallization.

Furthermore, another consideration for metallization is to have appropriate photoresist mask which will withstand the high temperatures that the wafer will be exposed during the metallization. For this purpose, after chrome etching, the wafers are hard baked by exposing the wafers to 110°C for 1.5 hours and then 150°C for 3 hours. This hard bake process removes the remaining coating solvent or developer improves the adhesion, chemical stability and makes the photoresist more durable for metallization and BOE, though it distorts the shape because of the shrinkage in the resist.

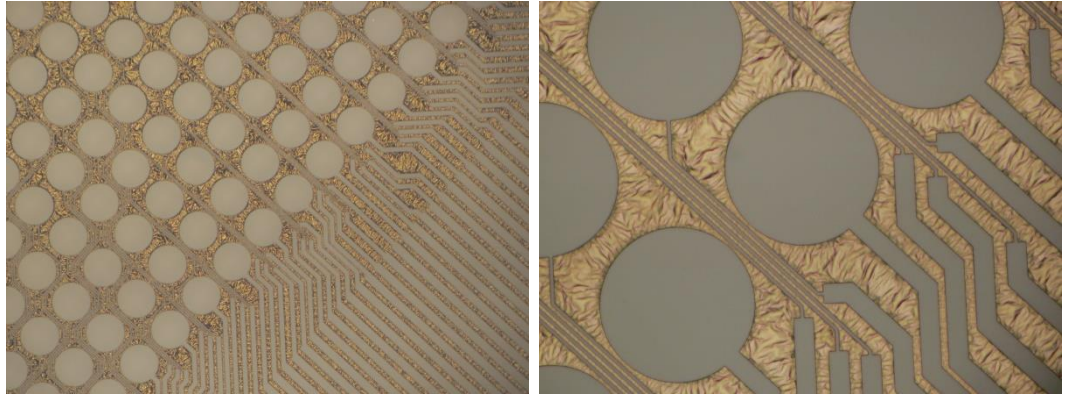


Figure 4.5: Microscope image after hard baking of the photoresist for 1.5 hours with 110°C and 3 hours with 150°C. Distortion of the shape on the photoresist can be seen.

After hard baking of the photoresist, dry etching with DRIE using SF_6 and argon plasma is done which approximately results in 480 nm of etch and in total of 730 nm cavity depth. From the 90 min trial process done on dummy wafer, the etch rate of the process is determined to be 6.44 nm/min. Thus, for approximately etching of 480 nm, 75 minute of ICP is done with the same recipe. After observing the environmental scanning electron microscope (ESEM) images, it is seen that undercuts are also formed after DRIE.

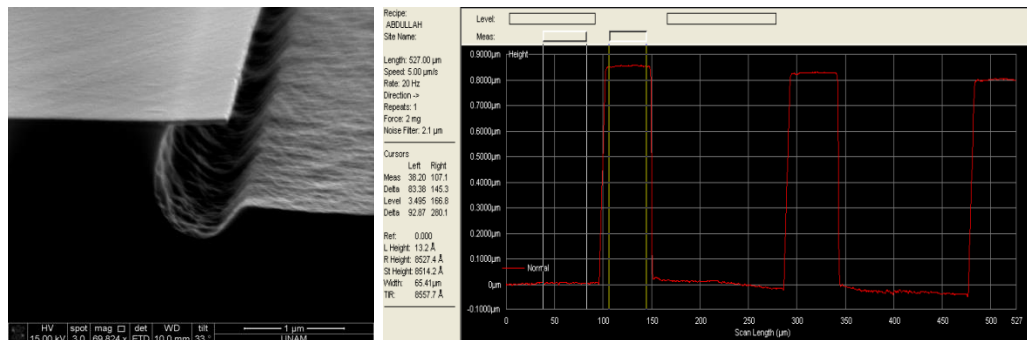


Figure 4.6: On the left side ESEM image after the dry etch process is shown. Undercuts are resulted after DRIE. The thin layer of metal is the chrome mask deposited at the beginning of the processes. On the right image, stylus profilometer result for the depth of the etched Pyrex cavity is shown for 90 minutes of DRIE with SF_6 and argon plasma. The chrome thickness is also

included in the measurement for greater comparison with the results obtained after ICP chrome etching.

After reaching an approximate depth of 670 nm in the cavities to form bottom electrodes, remaining 130 nm is decided to be etched by BOE. For this purpose, four samples that are neighbouring each other are chosen from the dummy wafer and BOE is applied for different time intervals in an incremental manner. First sample is preserved without applying any BOE, but for the others 4, 5 and 6 minutes of BOE are applied respectively. From this procedure etch rate of BOE at the time of the process is determined to be approximately 21 nm/min. Thus, the BOE duration is designated as 6 minutes, which results in approximately 126 nm.

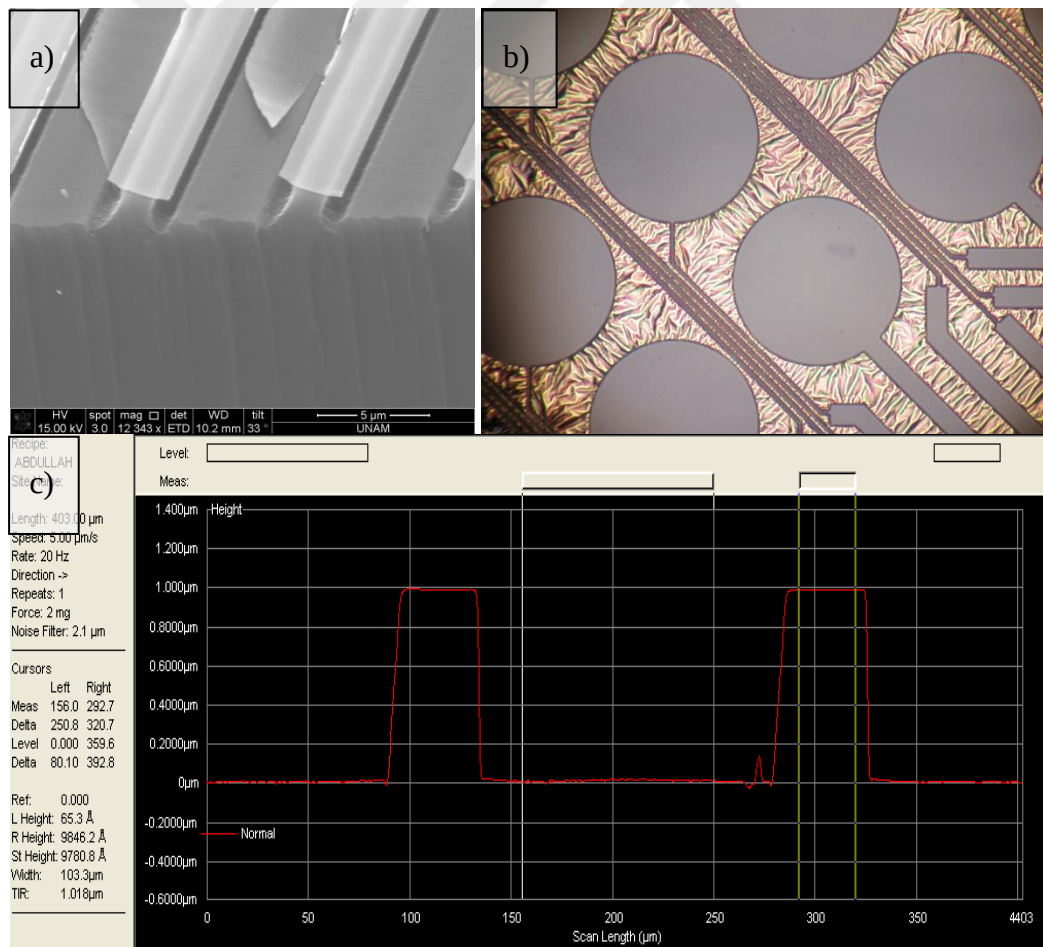


Figure 4.7: (a) ESEM image after applying 6 minutes of BOE. Cross-sectional view of the 3 μm wires can be seen. Residues are due to the cracking of the

wafer. (b) Microscope image after wet etching with BOE. (c) Sytlus profilometer measurement showing that the depth of the cavity is increased from 851 nm (Figure 7) to 978 nm by applying 6 minutes of BOE (≈ 127 nm of etching, which is consistent with the calculated etch rate). The chrome thickness is also included in these measurements for easier comparison with previous results and data.

It is important to remind that according to the high number of dependent variables that are affecting the etch rates and accuracy of the processes, each process step is done successively without leaving very long time periods. By this way the error between the expected and the actual values are minimized.

4.2.2 Bottom Electrode

After reaching a cavity depth of approximately 800 nm, in order to obtain gap height of 100 nm, metallization is completed accordingly. As explained earlier, 100 nm of Titanium as adhesion layer, 100 nm of Platinum as barrier layer and 500 nm of Gold as low DC resistance electrical connection layer is deposited by using MiDAS PVD 1eB e-beam evaporator (Ankara, Turkey).

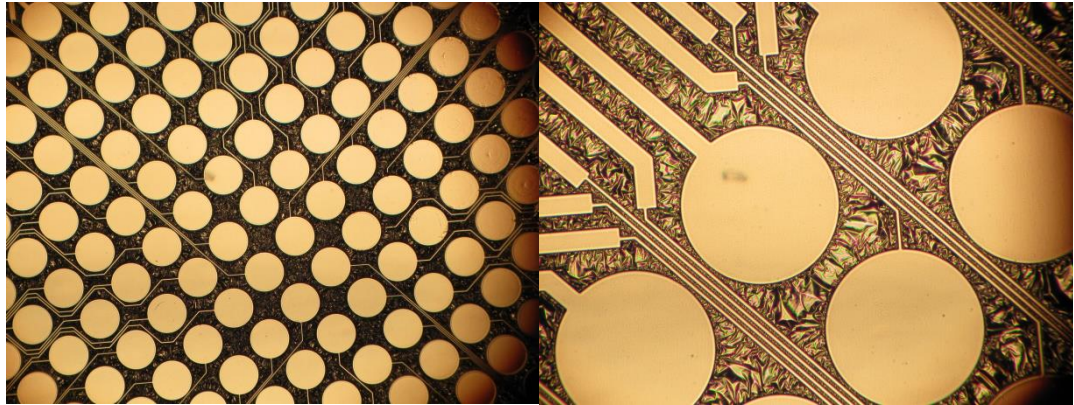


Figure 4.8: Microscope images after depositing 100 nm Ti, 100nm Pt and 500 nm Au (before lift-off).

Because of the high melting point of Platinum, before and after depositing this material, vacuum chamber is left for cooling. For each material, deposition is started after the chamber pressure reaches maximum of 2.0×10^{-6} Torr. Also by

not breaking the vacuum and depositing all the materials in a single run adhesion between materials is improved. Titanium is deposited with a rate of 1 Å/second, Platinum with a rate of 1.5Å/second and Gold with a rate of 2.5 Å/second. Between each deposition vacuum chamber left for cooling for 30 minutes. By this way, both the deformation on photoresist is minimized and pressure of the chamber decreases down to 4.0×10^{-7} Torr.

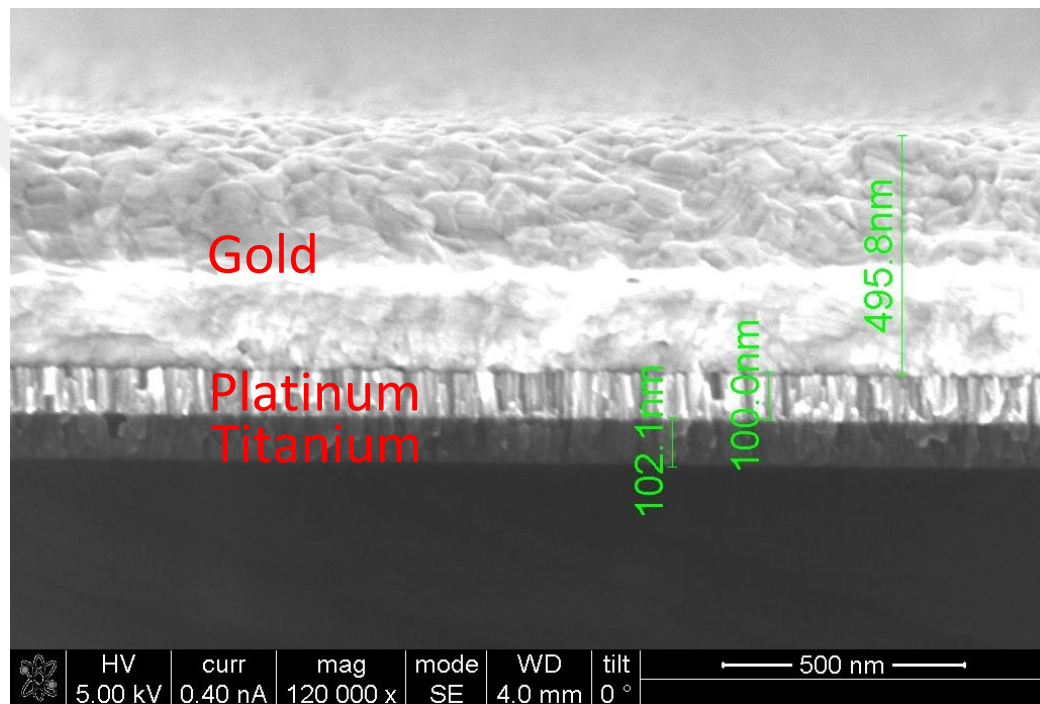


Figure 4.9: Focused ion beam (FIB) image of the cross-section of the Ti/Pt/Au stack deposited on silicon sample.

After deposition is completed lift-off is done by using Piranha wet etch. On three units of sulphuric acid (H_2SO_4) and one unit of hydrogen peroxide (H_2O_2) is slowly poured in order to obtain the Piranha solution. This strong mixture etches the organic components such as photoresist which results in lifting off the gold on top of the photoresist areas and leaving the cavities with desired metal connections. However, since Piranha solution also slowly etches titanium, some of the wires with 3 μm width, are also lifted off. In order to prevent this excessive exposure of the wafer in this solution is avoided. After removing all the photoresist and Ti/Pt/Au stack from the necessary regions, chrome wet etch

is done by using CR-7 (Sigma-Aldrich, Taufkirchen, Germany). Due to the high attacking rate of this solution to chrome regions, this process is swiftly completed and lift-off process is finalized by leaving Pyrex and gold on top of the wafer.

Lastly, insulator layer is deposited in order to form the top layer on the substrate and also the adhesion layer for the wafer bonding process. This layer is necessary in order to avoid short-circuit if any unintended collapsing occurs. Thus, to prevent any change in the gap height and continuity on the wafer surface, Alumina (Al_2O_3) is deposited with atomic layer deposition (ALD). Savannah Thermal ALD (Veeco, Plainview, NY) is used with a predetermined and recommended recipe. With this recipe in each deposition cycle $1.005 \text{ \AA}$ thickness of alumina is deposited. According to the previous researches, ALD deposited alumina's dielectric breakdown strength is measured to be 640 kV/mm . In order to have a safety margin as twofold of collapse voltage, required insulator thickness is calculated to be 300 nm , which results in 192 volts dielectric breakdown voltage. Thus, with the mentioned recipe, 3000 cycles of deposition, which approximately lasts for 14 hours to execute, is done. Due to the transparent structure of alumina, only a small colour change could be observed with a slight blue reflection under appropriate lighting.

Final process on the substrate is to etch the insulator, alumina, from the electrical connection pad regions. The insulator should be etched since gold stud bonding is done on these areas for flip-chip bonding. Second lithography mask is used for this purpose. Although the pad areas were relatively large ($500 \text{ }\mu\text{m}$ squares) and shadow mask alignment can be sufficient, a conventional chrome lithography mask is used instead for better alignment and ease of processing.

Etching of alumina is done by using the same developer solution that is used for developing AZ4562 positive photoresist, which is four units of DI water and one unit of AZ400K. However, this process lasts approximately three hours. Hence, only using the photoresist as etch mask in order to etch alumina is

also etches the photoresist. This results in etching of alumina over undesired regions. To prevent this chrome hard mask is used again.

Over the insulator layer, alumina 50 nm of chrome is deposited with e-beam evaporation. Over the chrome layer HMDS and AZ4562 positive photo resist are spin coated with same specifications that is used in the first photo-lithography process. After pre-baking of photoresist, UV exposure of 70 mJ/cm^2 is applied with using the second lithography mask. By using the same developer solution, photoresist is developed for 5 minutes. When the features are clearly constructed with photoresist, chrome wet etch is conducted to etch the chrome from the electrical pad connection regions. After reaching to alumina on the electrical pad connection regions, wafer is kept in 4:1 AZ400K solution for three hours. The colour change on these regions due to the etching of the alumina is observed by microscope. However, for further verification of successful and complete etching of alumina on these regions, probe station is used by checking the DC resistance on these pads. After successful etching, remaining photoresist (if there is any) is etched by acetone and the chrome hard mask layer is again etched with CR-7 chrome wet etch. Finally, on the substrate, the insulator layer of alumina remains as the top layer on the Pyrex wafer except the electrical connection pad regions where the top layer is gold.

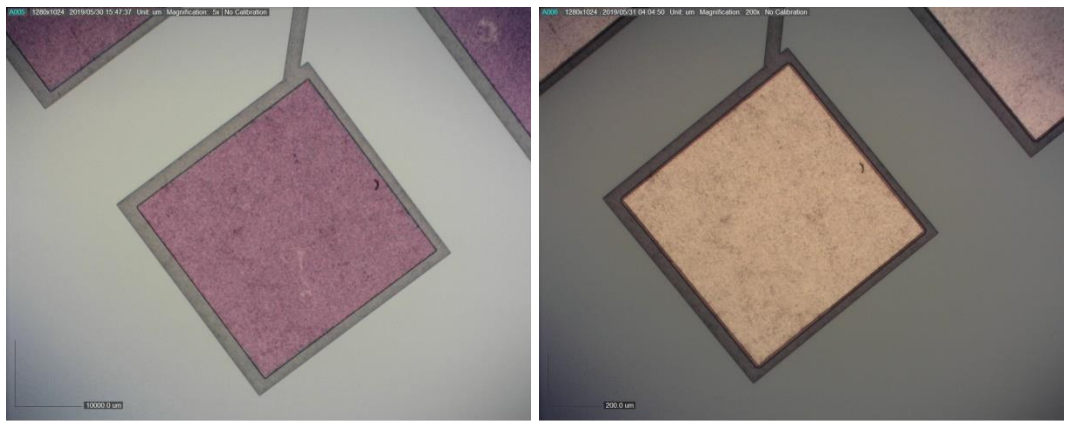


Figure 4.10: (a) Before and (b) after etching the insulator layer, Alumina.

At this stage, wafers are prepared for wafer bonding. Before the wafer bonding process microscope images are taken for each device and also two

different profilometer measurements from two different places on the same device is taken in order to determine the final gap height values for further simulation measurement verifications. From Figure 4.11, it can be seen that there is a colour difference between two wafers. This is due to the surface roughness difference. On wafer 2, the gold deposited surface is rougher compared to wafer 1. However, the maximum derivation on the gold surface of wafer 2 is approximately 15 nm. After depositing Alumina colour difference becomes more significant, however, it is due to the light scattering and reflection from microscope on sub-nm structures.



Figure 4.11: (a) Wafer 1 and (b) Wafer 2 substrate before wafer bonding.

Finally, two wafers are sent to EVG Austria facilities for wafer bonding with 15 µm device layer SOI wafers. These two wafers are consisting of 42

devices in total and for each of these devices profilometer measurements are conducted. All these devices are numbered according to the Figure B.48. From now on, each device is referenced according to this numbering and placement.

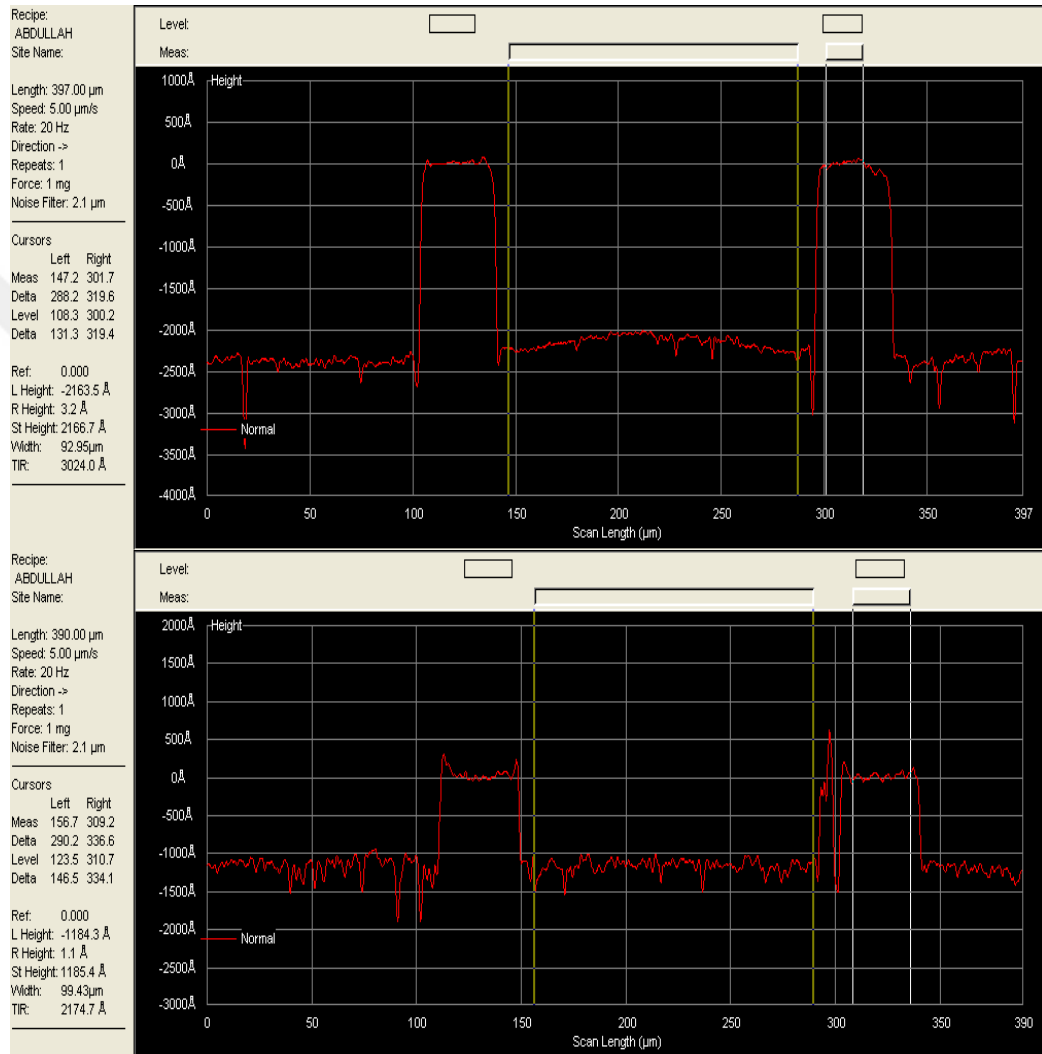


Figure 4.12: Stylus profilometer measurements from (a) wafer 1 – 11th device and (b) wafer 2 – 15th device, which results in 216.7 nm and 118.5 nm gap heights respectively.

4.2.3 Wafer Bonding & Top Electrode

Wafer bonding process is conducted in EVG Austria facilities. For this process, two Pyrex wafers with different gap heights are used. For the membrane layer, SOI wafer with 350 μm handle layer, 1 μm BOX layer and 15

μm device layer of silicon is used. Surface defects on both Pyrex and SOI wafers such as residues, particles and scratches could be observed before wafer bonding, which are possible reasons for local bonding defects. EVG® 520IS 200mm semi-automated wafer bonding system is used for wafer bonding processes. After cleaning of both wafers with DI water and megasonic nozzle mechanical edge alignment is done, which will be followed by the wafer bonding.

First wafer bonding process is done firstly on the wafer 2, where no yield could be gathered. Only around 50% wafer surface was bonded. In the first bonding process it is observed that while the regions where the electrical connection pads, which are $500\ \mu\text{m}$ squares, are located the bonding process is successful. However, the regions where the CMUT elements are located, bonding was not maintained. According to this observation, it is determined that the ion flux through SOI wafer to Pyrex wafer is not sufficient to maintain a successful bond over the regions where CMUT elements and $3\ \mu\text{m}$ wirings are located. Thus, keeping these two wafers under bonding recipe for a longer period of time would result in higher ion flux in these narrow regions and successfully bond with SOI wafer's device layer. With this determination wafer 2 is re-bonded with increased temperature and voltage. An increase in bonded area was achieved. The root cause of the unbonded area might be the surface defects observed during incoming inspection and the material nature that electrical potential is difficult to move the carrier ions from alumina to silicon.

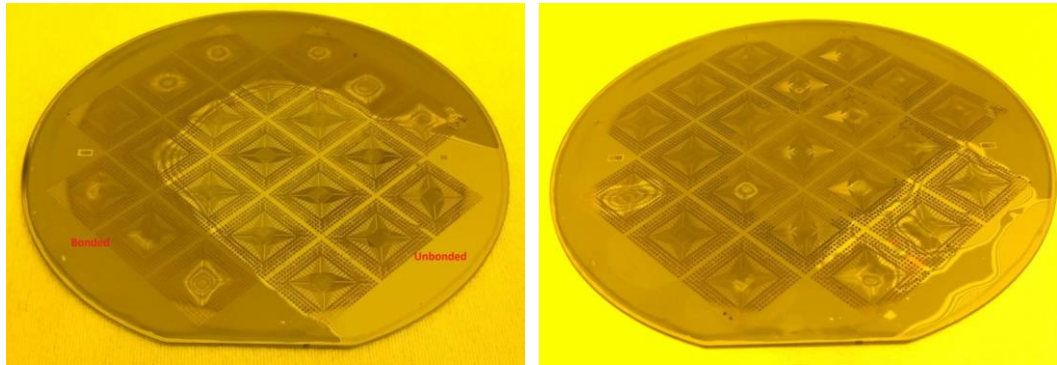


Figure 4.13: Bonded and unbonded areas are shown for wafer 2 for the first (a) and second (b) bonding process with increased temperature and voltage.

According to the observations made on wafer 2, second wafer bonding process is done on wafer 1 with a similar recipe that is applied on the last try on wafer 2. The bonding was processed with a modified recipe with 1000 volt and at 450°C. The bonding result is good with only a few minor defects at the wafer edge, which is caused by the residues on the wafer surfaces.

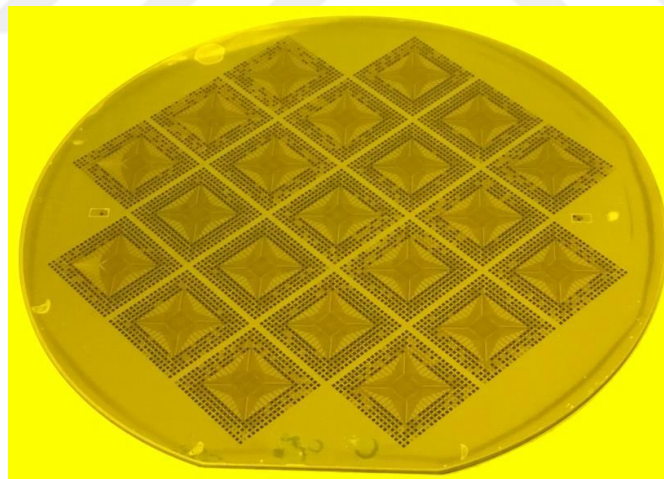


Figure 4.14: Wafer 1 after wafer bonding with the modified recipe of 1000 volts and 450°C.

Even though the bonding between Pyrex surface under alumina and silicon layer is successful over the entire region, incomprehensible defects over the metal regions are formed after wafer bonding process, where some metals are defected and some are remained undamaged.



Figure 4.15: Defects on metals of electrical connection pads after wafer bonding process.

After receiving the wafers from EVG Austria, firstly the silicon handle layer with 350 μm thickness is etched by DRIE with SF_6 plasma. Thirteen cycles with 20 minutes of periods are applied over the wafer in order to completely etch the handle layer.

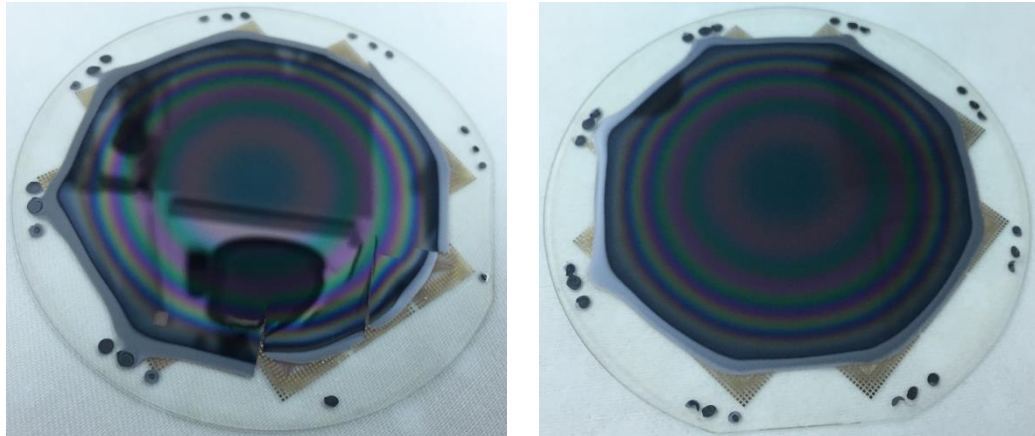


Figure 4.16: Wafer 2 (a) and wafer 1 (b) after 350 μm thick handle layer removal with SF_6 plasma DRIE.

When the handle layer over the BOX layer is completely etched, silicon dioxide (BOX layer) is etched by BOE wet etch. After completely etching the silicon dioxide, device layer of 15 μm silicon which will be the CMUT membrane is reached. Due to the low conductivity of silicon membrane, it is

determined that current that will flow to the ground pads will face with a high resistance. In order to prevent this, 30 nm Cr, 40 nm Au, and 30 nm Cr stack is deposited over the entire wafer surface. Finally, the ground pads on the silicon membrane are deposited by using a shadow mask. Since the ground pads are 1 mm squares and the clearance between the nearest features over the wafer surface is 1 mm, shadow mask is an easy and low cost option for metal deposition. Thus, by using shadow mask, 30 nm Cr and 500 nm Au stacks is deposited on the membrane.

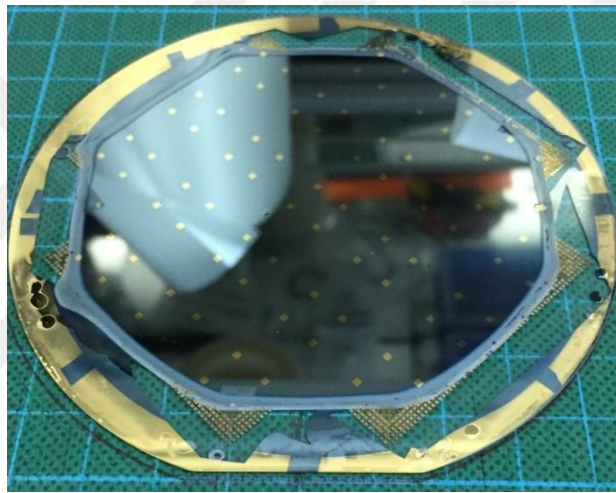


Figure 4.17: Wafer 1 after metal deposition with shadow mask.

After depositing the top electrodes for ground connection, bottom electrodes underneath the Cr-Au-Cr stack and silicon device layer. For this purpose, the same lithography mask used for etching the alumina regions over the electrical pad connections is used again. Since the photoresist will be etched with a dry etch process in ICP, AZ4562 photoresist is not used but instead a thinner photoresist, Microchemicals AZ5214E (Ulm, Germany) is used as positive photoresist. Approximately 2 μm of AZ5214E is spin coated after HMDS spinning and UV exposure is conducted with same parameters that are used for earlier photolithography steps. After successful development of the photoresist with AZ400K Cr-Au-Cr stack should be etched with a wet etch process. Thus, both chrome layers are etched with CR-07 and gold is wet etched

by using diluted Aqua Regia solution (3:1:2 mixture of hydrochloric acid, nitric acid and DI water) with DI water rinsing in between each etch process.

When the silicon layer is reached, dry etch process is conducted by using ICP. For this dry etch process, DRIE Bosch process is chosen to be appropriate in order to maximize the anisotropic etching [50]. Approximately applying the Bosch process for 16 minutes, silicon device layer on the electrical pad connection regions are completely etched.

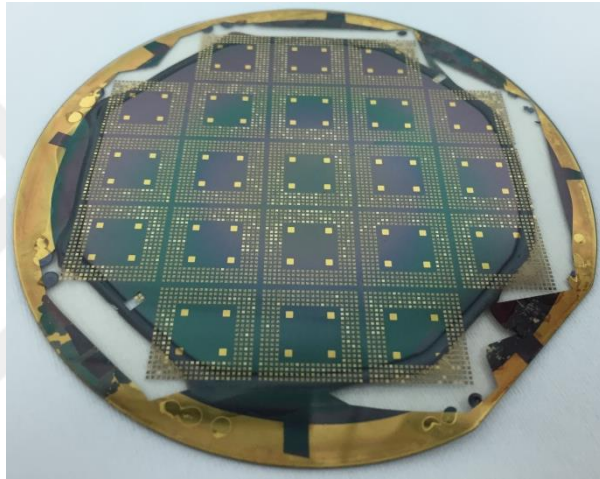


Figure 4.18: Wafer 1 after silicon dry etch with DRIE Bosch process.

The last step before dicing of the wafer is to strip the photoresist. Since the gaps are unsealed after dry etching silicon, wet etch for stripping PR is not an appropriate choice. Thus, for etching the photoresist, O_2 plasma in ICP tool is used. Approximately in 17 minutes photoresist over the entire region is stripped with dry etch process, however, O_2 plasma also attacks chrome layer under the photoresist. Thus, the final top layer of the wafer is remained with the gold top electrodes for ground connection and resistance reduction layer of gold.

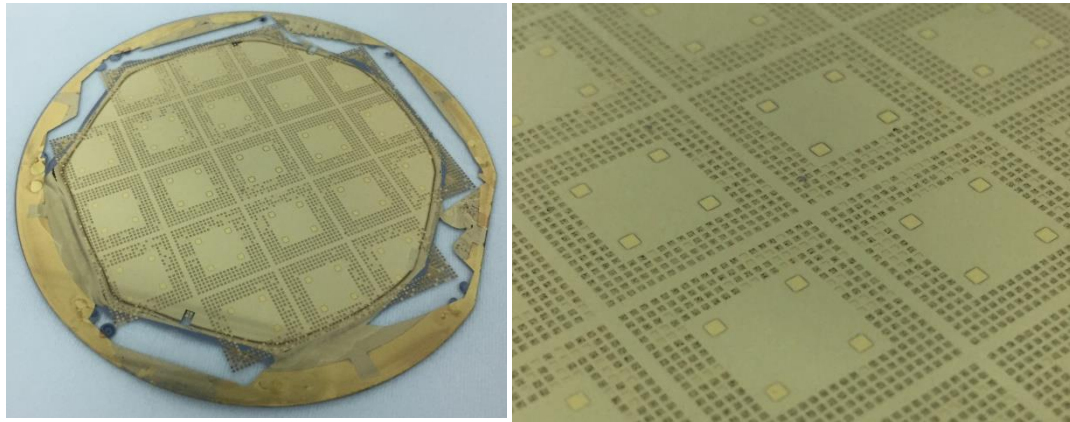


Figure 4.19: Wafer 1 after photoresist stripping and chrome etch with O₂ plasma dry etch.

Finally, the devices on the wafers are diced by using UV curable dicing tape of Adwill D series (Tokyo, Japan). Wafers are placed on the dicing tape with wafer's backside facing upwards and dicing is not conducted over the total thickness of the wafer but instead half of the wafer is diced. By this way any damages that can occur on the membrane formed with wafer bonding is prevented. Also during the dicing process, since DI water is sprayed over the whole wafer, in order to prevent leaking water through unsealed gaps, wafer is placed upside down over the dicing tape. After the dicing, dicing tape is exposed to UV light to reduce its adhesion and by this way devices could be diced without damaging the 15 μm membrane.

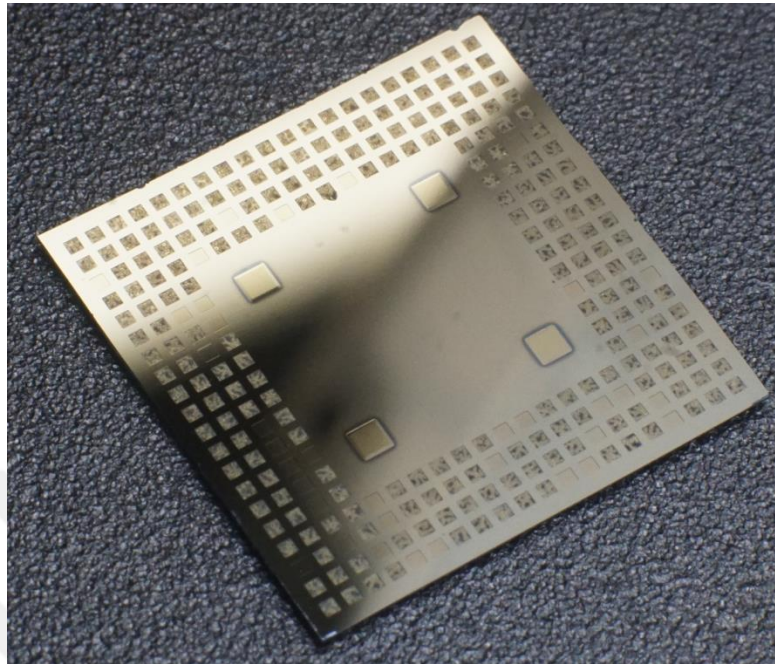


Figure 4.20: Finalized MEMS chip of 16×16 CMUT phased array.

4.2.4 Flip-Chip Bonding & Sealing

Previously it is planned to flip-chip bond the devices to designed PCBs with using Finetech FINEPLACER[®] sigma (Berlin, Germany) with its ultrasonic arm and after bonding the sealing was planned to be done with Parylene-C coating. However, with the ultrasonic arms maximum ultrasonic power of 20 Watt is not sufficient to bond 256 gold ball bumps. Thus, as an alternative it is decided to use SMD adhesive to mechanically bond the MEMS chip and the PCB. For this purpose, Martin SMD Adhesive D 125 F-DR (Germering, Germany) is used. However, using this adhesive also prevents to seal the bonded device with Parylene-C since the available Parylene-C coater tool cannot be used with non-bio-compatible materials.

After placing 256 gold ball bumps on the PCB's necessary connection pads, MEMS chip is aligned to gold ball bumps on flip-chip bonder tool. SMD adhesive is applied on the areas where no connection interference or contamination may occur with flip-chip bonder tool's dispenser. Then the

bonding recipe is applied with 20 Watts of ultrasonic power for 500 ms, 15 Newtons of force and 120°C for 2.5 minutes for successful curing of the SMD adhesive. With this procedure, bonding of each 256 connection points cannot be guaranteed but according to sample processes significant amount of connection is maintained with this mechanical bonding process. Although the optimal parameters for ultrasonic power per bump is 1.5 Watts and 0.49 Newton of force per bump at 200°C, only 16 bumps could be bonded with these parameters [51].

After flip-chip bonding of the MEMS chip and the PCB, wire bonding for the ground pad connection on the PCB is done. After wire bonding in order to prevent any damage on the wires, EPO-TEK T7139 glob top epoxy (Billerica, USA) is applied.

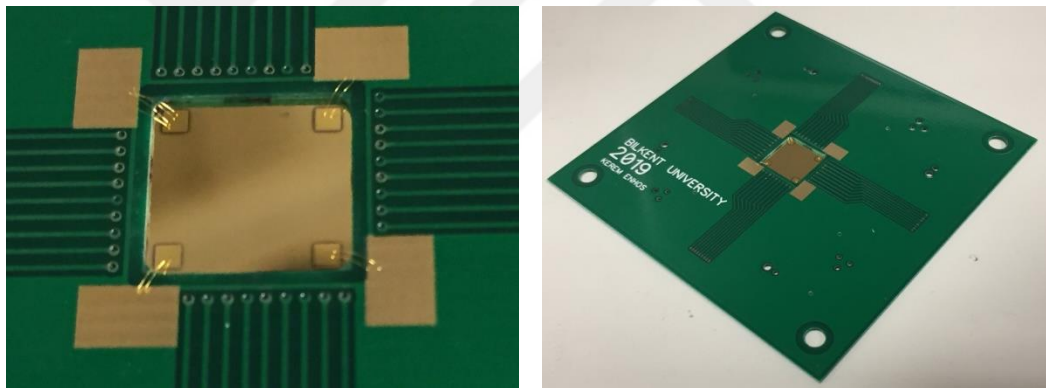


Figure 4.21: Wire bonding of ground connection pads and flip-chip bonded device.

When the MEMS chip is successfully bonded to PCB and ground pads are connected and protected with glob top, final step is the sealing of the device. With usage of non-bio-compatible materials such as SMD adhesive or any other epoxy, prevents the sealing with Parylene-C. Thus, for sealing another epoxy is used. Since there is 3 μm features that should be sealed, using a low viscosity epoxy is beneficial for successful sealing. For this purpose, EPO-TEK 310M flexible optical epoxy is used. After applying sufficient amount of epoxy over the backside of the MEMS chip and PCB cross-section, whole device cured in vacuum conditions for 24 hours.

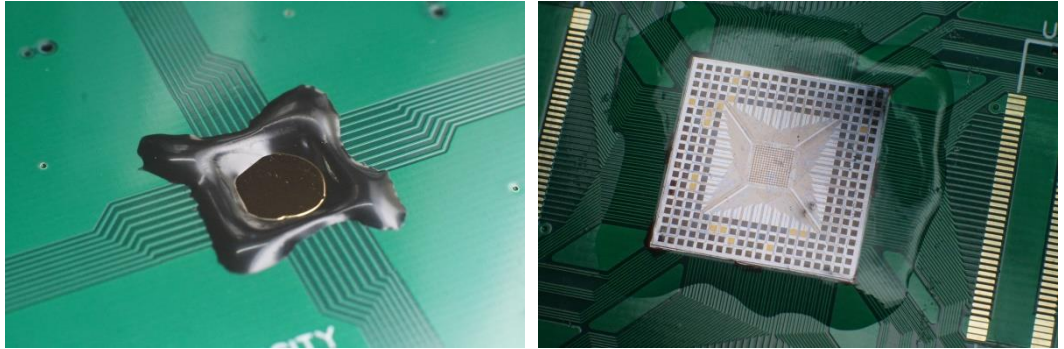


Figure 4.22: Front side (a) (transmission side) and the backside of the bonded MEMS chip and PCB.

Finally, after sealing devices, bonded MEMS chip and PCB is integrated into a probe by using a 3-D printed casing. By connecting all the necessary coaxial cables, fabricated device is ready for measurements.

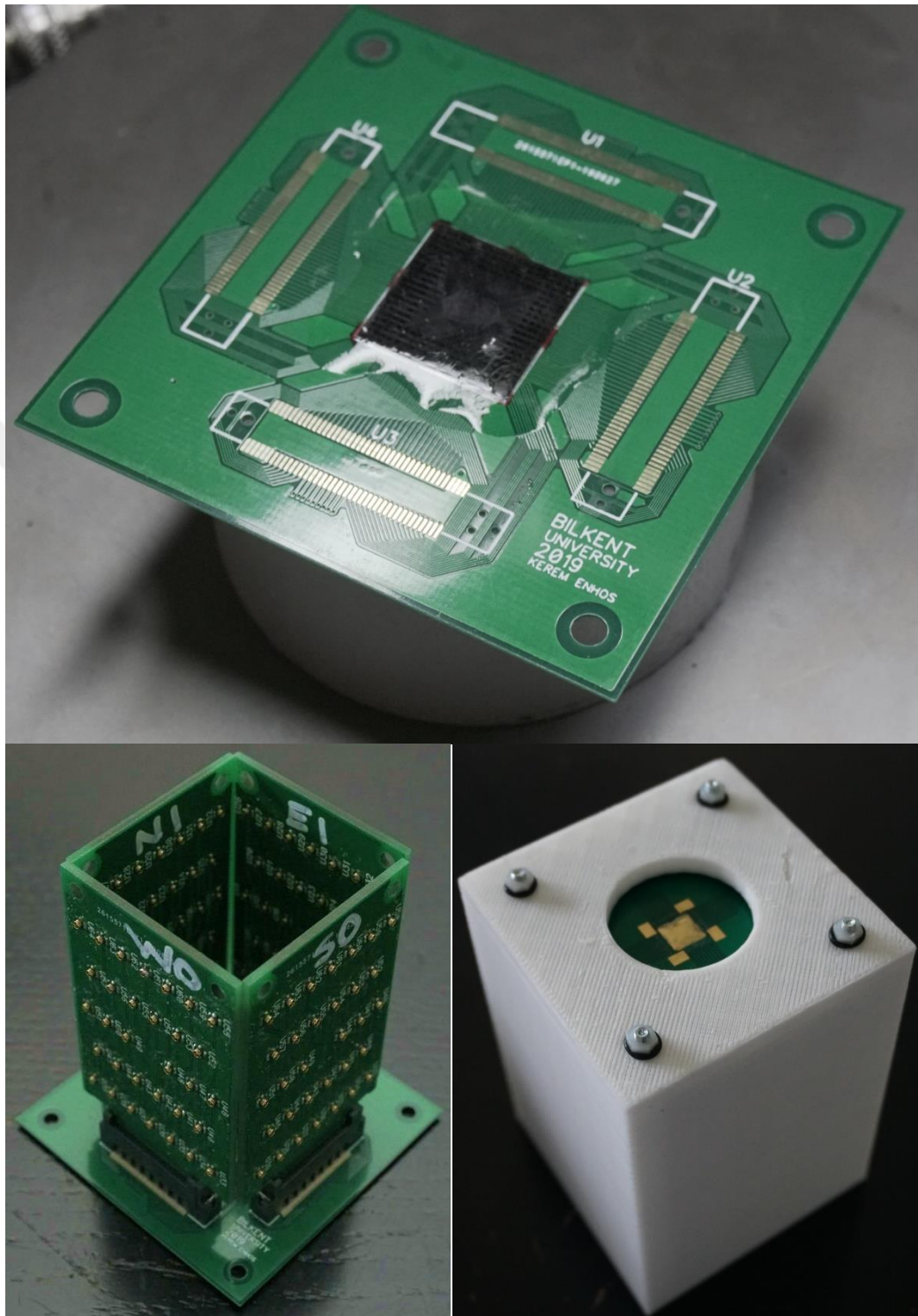
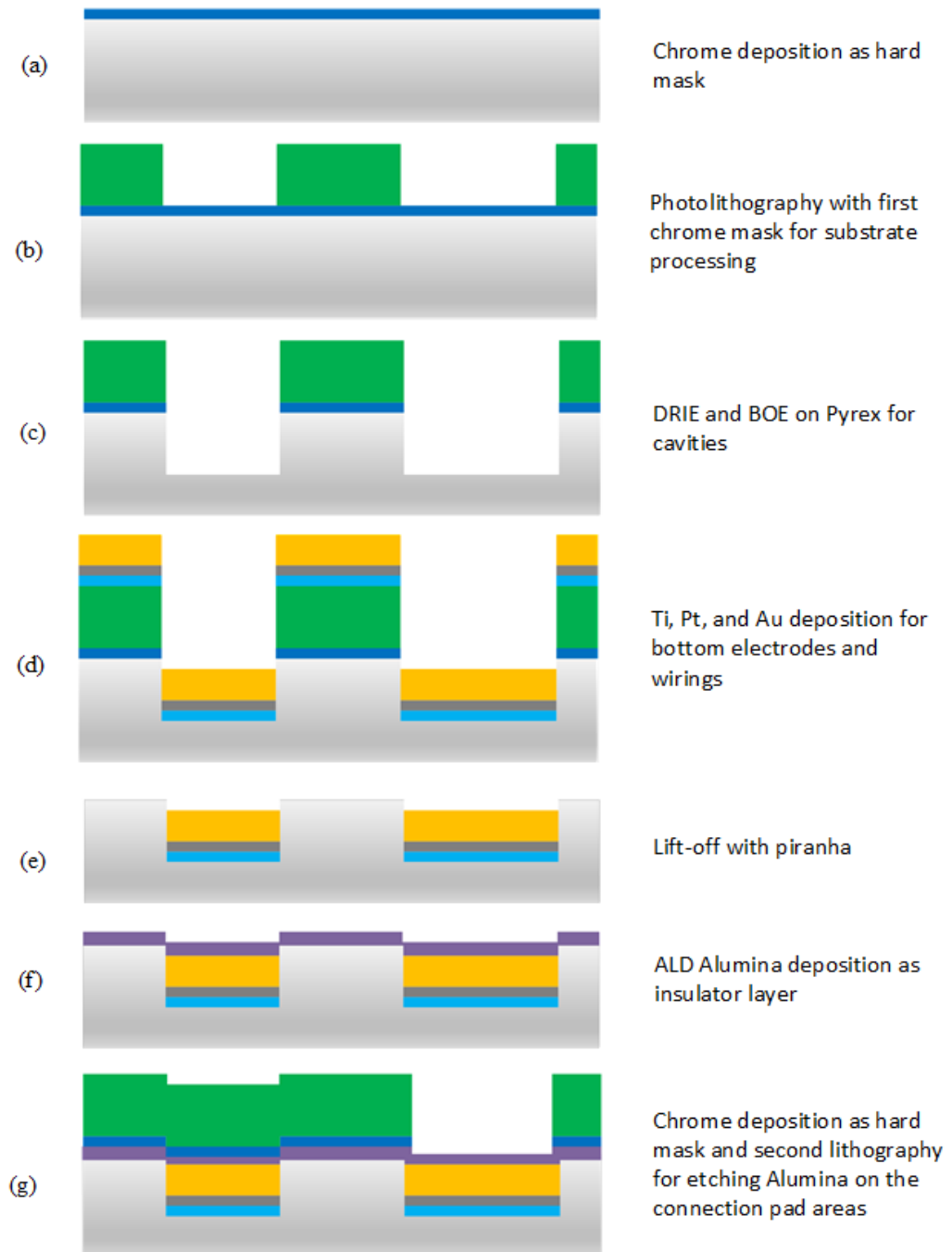


Figure 4.23: Probe integration.

4.2.5 CMUT-MEMS Fabrication Overview



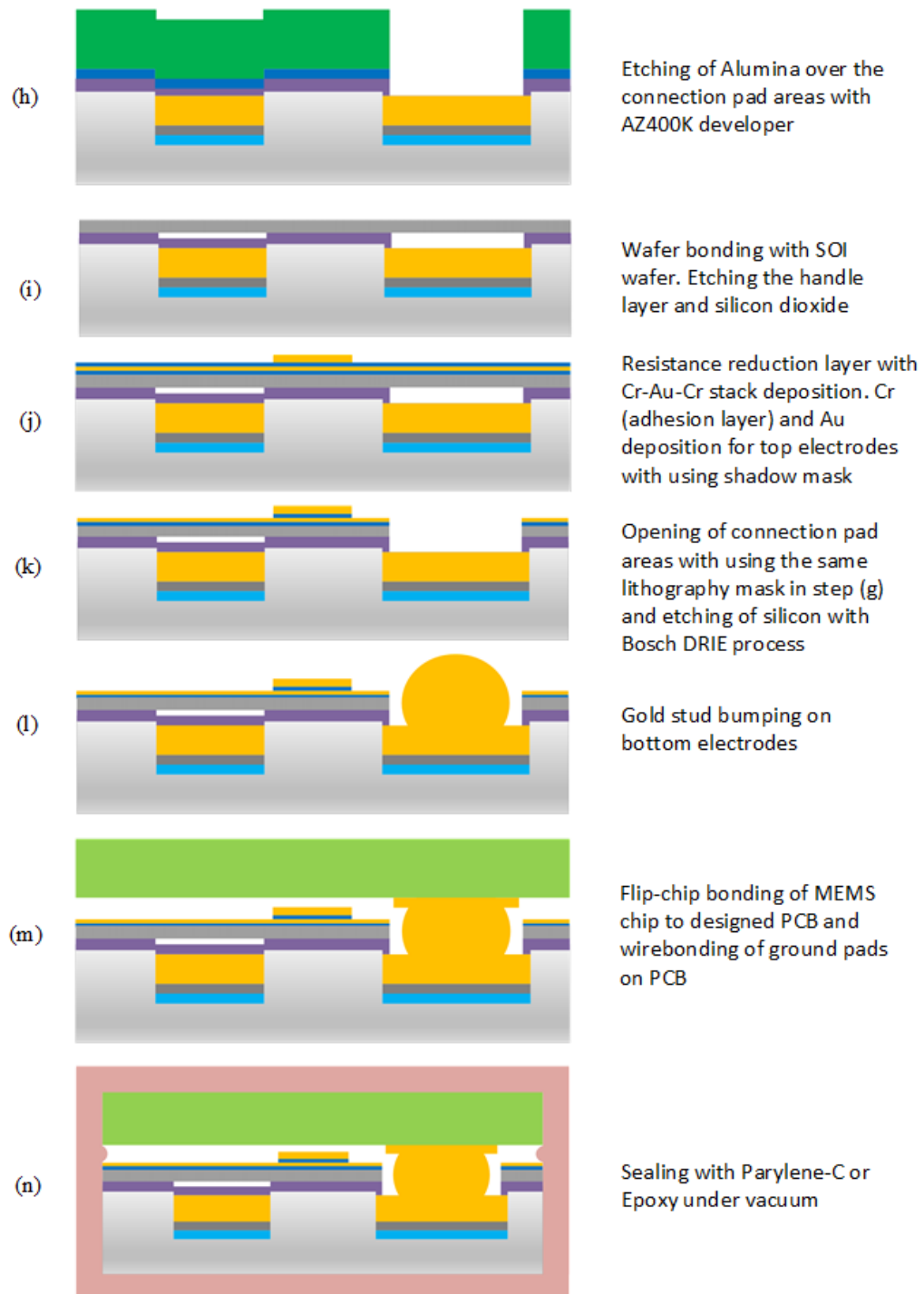


Figure 4.24: Fabrication flow of CMUT arrays manufactured at Bilkent University.

Chapter 5

Measurements

5.1 Impedance Measurements

After fabrication of the devices, firstly the impedance measurements are conducted with HP4194A impedance analyser (California, USA). According to the simulations presented in 3.3 Impedance Simulations, it is known that the conductance values are significantly low for accurate measurement. Thus, because of the high difference in the intrinsic acoustic impedance of silicon membrane and air, admittance measurements are conducted in air. By this way, it was possible to realize resonances with DC bias input.

Impedance analyser's maximum AC output voltage is 1 volt, which is significantly low for characterization of unbiased mode of operation. Thus, DC bias voltage of maximum 40 volt is applied with 0.5 V_{ac}. By this way, resonances between 6 and 8 MHz are observed differentiating for each CMUT cell. It is also realized that significant amount CMUT elements are shorted with ground or connection between MEMS chip and PCB could not be maintained during the fabrication process. CMUT elements that have proper connection are marked and each cell's admittance is measured and recorded. All measurements are taken on the 7th device of wafer 1, which gap height information and placement on the wafer can be seen in B.2 Extra Fabrication Graphics.

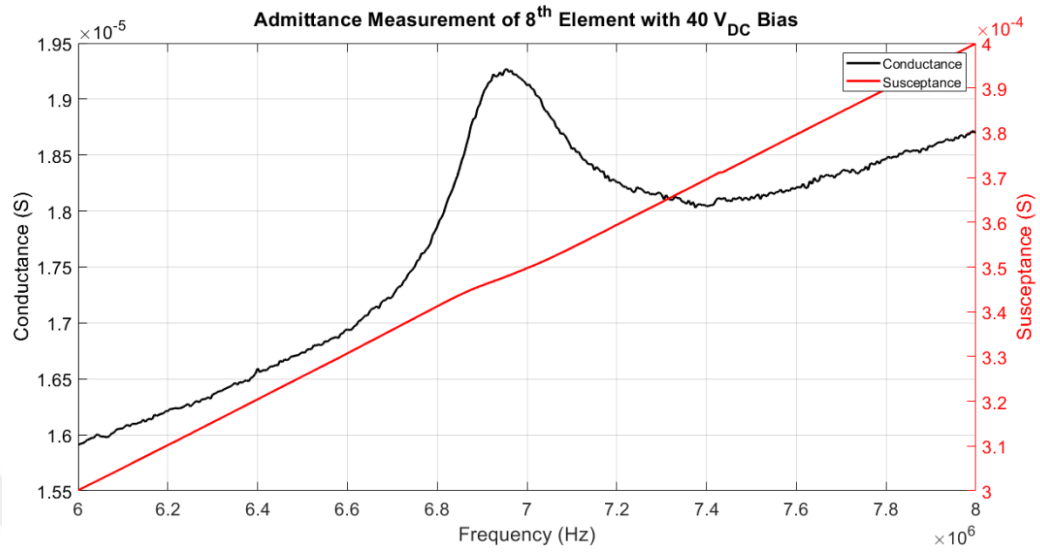


Figure 5.1: Admittance of 8th element of the 7th device. Resonance is measured at 6.94 MHz with 19.24 μ S in air.

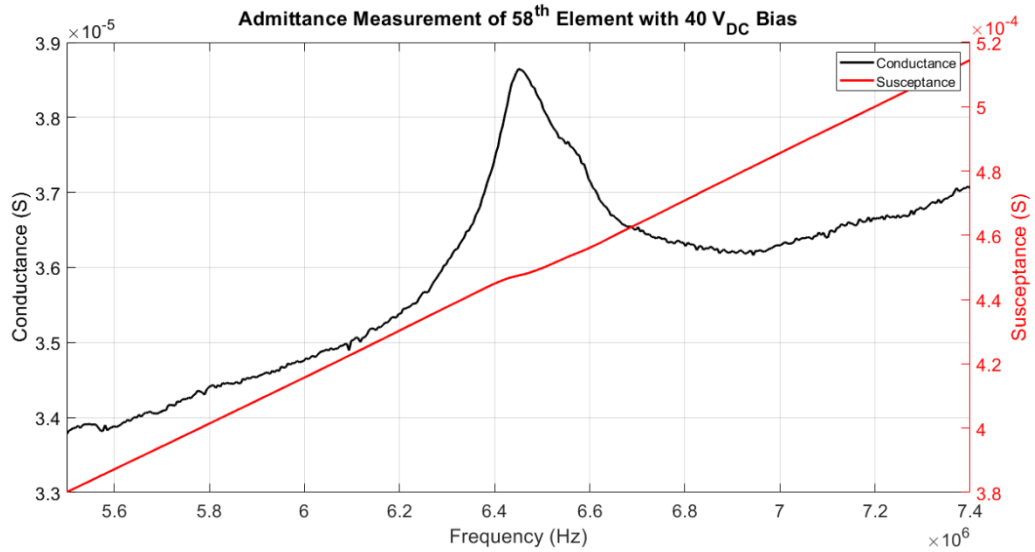


Figure 5.2: Admittance of 58th element of the 7th device. Resonance is measured at 6.45 MHz with 38.65 μ S in air.

According to given measurements it can be realized that the resonance frequencies are similar to the peak frequency that is shown in the harmonic balance analysis for waterborne simulations of the array. It is expected to have higher frequency resonances in airborne compared to waterborne measurements; however, in this set of measurements, the resonance frequency was measured to

be at 6.3 MHz, which is equivalent to the peak frequency of the harmonic balance simulations, 6.36 MHz. This phenomenon is fundamentally occurring by driving only one element of the array while all the other cells in the array remain as dummy cells. Presence of these dummy cells matches with the vibrations in the medium and also the radiation of the single excited cell. This matching removes the acoustic impedance difference between air and water, and the resonance frequency results at the mechanical resonance frequency of the array.

During measurements it is observed that CMUTs are charged during the fabrication process. It is realized with the 156th element in the array, when there is no DC bias, resonance peaks can be seen. At -10 V_{DC} it is observed that the resonance peak is completely disappeared, which means that the CMUT element is charged about 10 volts. For different DC bias levels, admittance is measured in air for this element as shown in Figure 5.3.

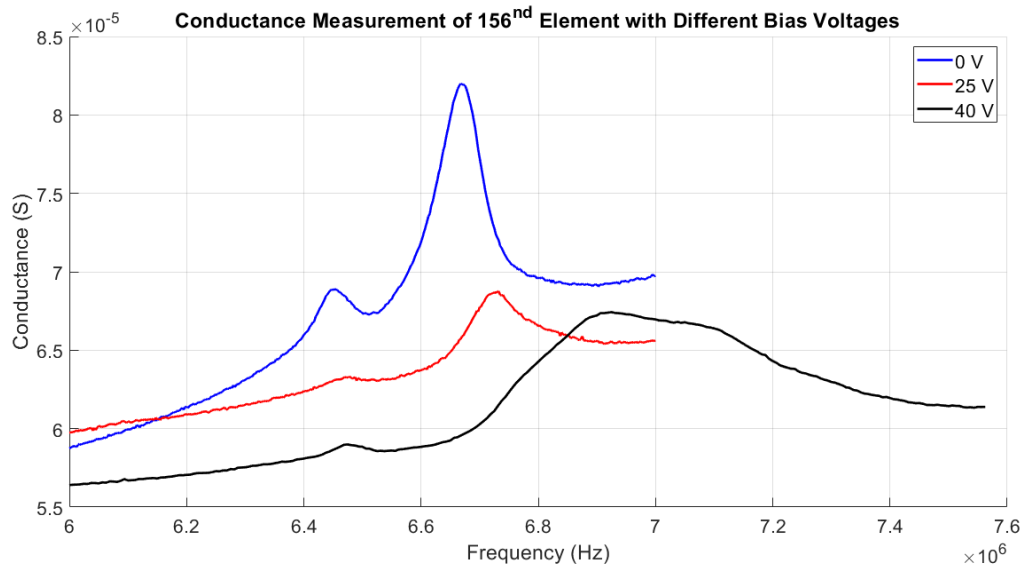


Figure 5.3: Conductance of 156th element of the 7th device. Change in resonance frequency and conductance level for different DC bias can be seen. At zero DC bias the resonances can be observed.

Further measurements could not been taken with ultrasound measurement system or in water because of lack of safety for the fabricated device and measurement setup. Although the final status of the device is appropriate for waterborne pressure measurements, further work should be done for more controlled environment and measurement setup.



Chapter 6

Conclusion

This thesis focuses on the design, simulation, fabrication and characterization of CMUT arrays with unbiased mode of operation. With the knowledge provided earlier on the unbiased operation mode on single airborne CMUT cell, design procedure extended for array configuration by using the large signal equivalent circuit model and mutual radiation impedance matrix for computing this array with fairly large number of elements.

For volumetric transmission 16×16 (256 elements) array configuration and 7.5 MHz operation frequency is selected considering the limitations and resources. Design and simulation is also completed for 18.5 MHz operation frequency transducer is also completed, however, it could not be mentioned within this work due to the lack of fabrication and measurement data though some parameters and method of fabrication are mentioned. In further works, these simulation and design results can be used. For 7.5 MHz operation frequency, by designating the design constraints, a design procedure examining the Rayleigh distance and sidelobe level is constructed. According to these two starting point for design procedure, remaining parameters for the physical dimensions of CMUT arrays are calculated using the derivations provided by the lumped element model for the large signal equivalent circuit. After analytically calculating each dimension parameter, fabrication limitations are considered again and infeasible values are calculated again iteratively for the optimum and feasible design.

Due to the high number of elements in the CMUT array, FEM simulations were considered as insufficient by considering the challenges in the required computational power and time. Thus, large signal equivalent circuit model made it possible to conduct the simulations with higher efficiency in terms of computational power and time with sufficient accuracy compared to

experimental results. By using the flexibility of the conventional lumped element circuit analyser software, high variety of simulations are conducted in ADS. Both the harmonic balance (frequency domain) and transient analysis are completed with different duty cycles and transmission waveforms. Also by using the outputs gathered by ADS is used as transmission input signals in beamforming toolboxes for further examination of beamforming, radiation pattern and field pattern analysis.

After obtaining the optimum design by considering the fabrication limitations, wafer scale batch compatible production is maintained for manufacturing these MEMS devices. As substrate Pyrex wafers are used and bottom electrodes are constructed on the substrate in a self-aligned manner. Only two lithography masks are used for only three conventional lithography steps. In addition one shadow mask is also used for top electrodes. Conventional anodic wafer bonding is used for maintaining the vibrating membrane. As a result highly efficient and expeditious fabrication flow is achieved with low number lithography masks and steps. Upon the completion of the MEMS fabrication, diced devices are flip-chip bonded to PCBs for having the macro scale connection of CMUT array to the ultrasound measurement system. After the flip-chip bonding the sealing is completed and these sealed devices are integrated into a 3-D printed casing suitable for waterborne experiments.

After completing the integration of CMUT array with PCB and the casing, firstly experiments are conducted with impedance analyzer. Static capacitance measurements are taken firstly for the verification of the successful bonding of the membrane and top-bottom electrode connection. Due to the low level of admittance in water, airborne measurements are supplied where some resonance frequency can be determined. Also the lack of sufficient flip-chip bonding tools prevented some measurements to be taken. As a further work, with efficient flip-chip bonding, waterborne experiments can also be completed and pressure measurements can be taken for simulation result comparison.

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Appendix A

MATLAB Scripts

Optimum radius and pitch finder

```
% Constraints
freq=7.5e6; % Operation frequency
c=1500; % Speed of sound
lambda=c/freq; % Wavelength
k=2*pi/lambda; % Wavenumber
theta=-pi/2:pi/360:pi/2;
n=16; % Row element number
ka=pi/4:pi/360:pi; % ka values that will be
scanned
a=ka./k; % Possible radius values
x=0.1:0.01:1; % Pitch scale factor
count=1;
z=1;
%%
list=zeros(4,length(a)*length(x));
for i=1:length(x)
    for j=1:length(a)
        % Center-to-center element pitch
        d=2*a(j)+2*a(j)*x(i);
        % Element radiation pattern
        d_e = 48.*besselj(3,k.*a(j).*sin(theta))./ ...
            ((k.*a(j).*sin(theta)).^3);
        % Array factor

d_a=((1/n).*(sin((n*pi*d/lambda).*sin(theta)))./ ...
    (sin((pi*d/lambda).*sin(theta))))).^2;
        % Array radiation pattern
        dp=abs(d_e.*d_a);
        dp(isnan(dp))=1;
        % Rayleigh distance calculation
        ray_dist=((n-1)*d+2*a(j))^2/lambda;
        % Sidelobe level calculation
        pks=findpeaks(dp);
        pks(end+1)=dp(1);
        pks=sort(pks, 'descend');
        sll=pks(1)/pks(2);
        % Place the calculated values into an array
        list(1,count)=a(j);
```

```

list(2,count)=x(i);
list(3,count)=ray_dist;
list(4,count)=sll;
list(5,count)=d;
count=count+1;
% Select the possible design parameters
% according to given constraints
if (ray_dist>0.045 && sll>20 && (d-
2*a(j))>32e-6)
    fil(1,z)=a(j);
    fil(2,z)=x(i);
    fil(3,z)=ray_dist;
    fil(4,z)=sll;
    fil(5,z)=d;
    z=z+1;
end
end
end
% Find the optimum values
[vR,iR]=max(fil(3,:));
[vS,iS]=max(fil(4,:));

```

Transmission Delay Calculations

```

function [delay] = delayCalculation(theta, phi,
depth, c0, transmissionType)
%*****
% delay:                Returned delay values
% theta:                Elevation plane angle
% phi:                  Azimuth plane angle
% depth:                Depth values
% c0:                   Speed of sound
% transmissionType:     Returns focused transmission
%                       delay if 1, if 0 plane wave delay
%*****
d=192e-6;                % Pitch
% CMUT element placement
xE=zeros(1,256);
yE=zeros(1,256);
xE(1)=-1.44e-3;
yE(1)=1.44e-3;
for i=2:length(xE)
    if rem(i-1,16)==0
        yE(i)=yE(i-1)-d;
        xE(i)=-1.44e-3;
    else
        yE(i)=yE(i-1);
    end
end

```

```

        xE(i)=xE(i-1)+d;
    end
end
% Distance calculation according to given parameters
r=sin(deg2rad(theta))*depth;
xF=r*cos(deg2rad(phi));
yF=r*sin(deg2rad(phi));
% Delay calculation
delayF = ((sqrt(((xE-xF).^2 + (yE-yF).^2 ) +
depth^2))./c0)./(1e-9);
delayF=round(abs(delayF-max(delayF)));

%% Plane Wave Delay Calculation
dPW=d*cos(deg2rad(theta))/c0;
delayPW=zeros(1,256);
count=0;
for i=1:256
    delayPW(i)=(count)*dPW./(1e-9);
    count=count+1;
    if (rem(i,16)==0)
        count=0;
    end
end
if(theta>0)
    delayPW=round(abs(delayPW));
else
    delayPW=round(abs(delayPW-max(delayPW)));
end
% Return the desired delay type
if transmissionType == 1
    delay=delayF;    % Focused delay
else
    delay=delayPW;   % Plane wave delay
end
end

```

Delay and Sum Beamforming

```

% ADS Input
[in, time]=source_input('\...');
% Calculate delay values
delay=delayCalculation(0, 0, 15.744e-3, 1500, 1);
% Time shift of array according to delay inputs
in1=[ in zeros(256, max(delay))];
in2=zeros(256,size(in1,2));
for i=1:256
    in2(i,:)=circshift(in1(i,:),-1*delay(i));
end

```

```

end
% Sum shifted arrays
xx=max(sum(in2));

```

Direction & Field Pattern in k-wave

```

% Modelling Sensor Directivity In 3D Example
% This function is part of the k-Wave Toolbox
% (http://www.k-
% wave.org) Copyright (C) 2010-2017 Ben Cox and
% Bradley Treeby
clearvars;
% Parameters
% create the computational grid
PMLsize=10;
Nx = 512 - PMLsize*2;      % number of grid points in
the x direction
Ny = 512*2 - PMLsize*2;    % number of grid points in
the y direction
Nz = 128 - PMLsize*2;      % number of grid points in
the z direction
dx = 32e-6;                % grid point spacing in the x
direction [m]
dy = 32e-6;                % grid point spacing in the y
direction [m]
dz = 32e-6;                % grid point spacing in the z
direction [m]
kgrid = kWaveGrid(Nx, dx, Ny, dy, Nz, dz);
% define the properties of the propagation medium
medium.sound_speed = 1500;  % [m/s]
medium.density = 1000;      % [kg/m^3]
medium.alpha_coeff = 2.17e-3; % Attenuation coeff
medium.alpha_power = 2;
medium.BonA = 4.96;         % Medium nonlinearity
kgrid.setTime(4001*4, 1e-9); % Simulation time
% define a square source element
source_radius = 8*6; % [grid points]
source.u_mask = zeros(Nx, Ny, Nz);
source.u_mask(end, Ny/2 - source_radius-2:Ny/2 +
source_radius- ...
1-2, Nz/2 - source_radius+1:Nz/2 + source_radius) ...
= 1;
for i=1:Nz
    if (rem(i,6)==0)
        source.u_mask(:, :, i)=0;
    else

```

```

        end
    end
    for i=1:Ny
        if (rem(i,6)==0)
            source.u_mask(:,i,:)=0;
        else
            end
        end
    end
    % define equally spaced point sources lying on a
    % circle centered at the center of the detector face
    radius = Ny/2-11;    % [grid points]
    points = 81;
    circle = makeCartCircle(radius * dx, points,
    [Nx*dx/2-dx, 0], ... pi);
    circle = [circle; zeros(1, points)];
    % find the binary sensor mask most closely
    % corresponding to the
    % cartesian coordinates from makeCartCircle
    circle3D = cart2grid(kgrid, circle);
    element=sum(sum(sum((source.u_mask))));
    % find the indices of the sources in the binary
    % source mask
    sensor_positions = find(circle3D == 1);
    % define a time varying sinusoidal source
    source.ux=source_input('...');
    source_original=source.ux;
    Z=medium.sound_speed * medium.density;
    source.ux=(source.ux)./Z;
    source.ux=(source.ux)./((pi*((80e-6)^2))*25);
    max_velocity=max(max(source.ux));
    clamp=[2.4 2.2 2 2.2 2.4; 2.2 1.2 1 1.2 2.2; ...
        2 1 0 1 2; 2.2 1.2 1 1.2 2.2; 2.4 2.2 2 2.2 2.4];
    clampREP= repmat(clamp,16);
    crepe=reshape(clampREP, 1, []);
    source.ux=source.ux.*((1-
    ((crepe'.^2)./(2.5.^2))).^2);
    % Define sensor mask
    sensor.mask = zeros(Nx, Ny, Nz);
    % run a simulation for each of these sources to see
    % the effect that the angle from the detector has on
    % the measured signal
    % If the sensor mask is defined according to the
    % circle direction pattern is simulated. For field
    % pattern simulation define entire desired plane as
    % sensors
    for source_loop = 1:points
        % select a point source

```

```

        sensor.mask(sensor_positions(source_loop)) = 1;
    end
    display_mask = source.u_mask + sensor.mask;
    % run the simulation
    input_args = {'PMLSize', PMLsize, 'DisplayMask', ...
        display_mask, 'PlotScale', 'auto', 'PlotFreq', 50, ...
        'DataCast', 'single', 'PMLInside', false, ...
        'PlotPML', false};
    sensor_data = kspaceFirstOrder3D(kgrid, medium,
    source, sensor, input_args{:});

```



Appendix B

Extra Graphics

B.1 Extra Simulation Graphics

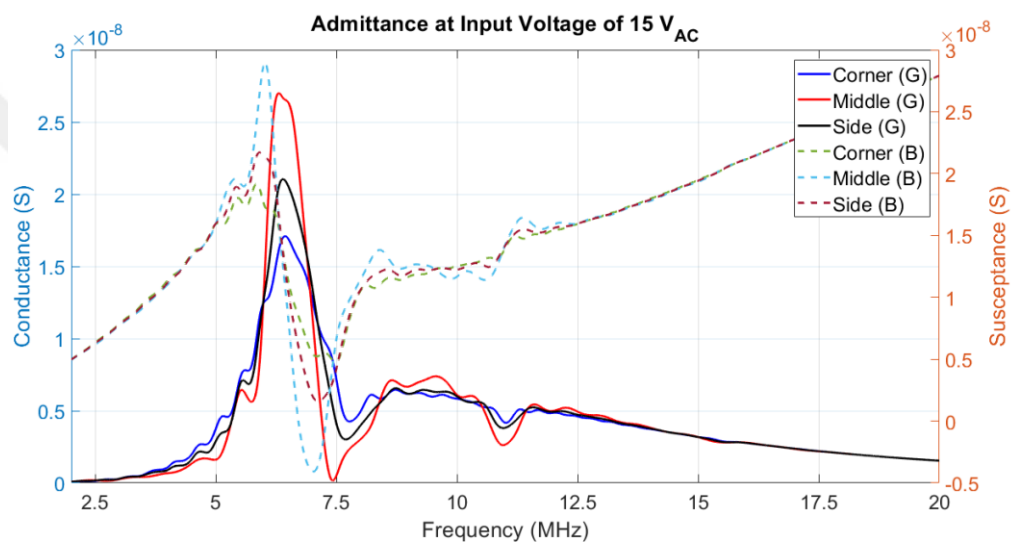


Figure B.1: Admittance at 15 V_{ac} input voltage. Susceptance values are shown in dashed lines.

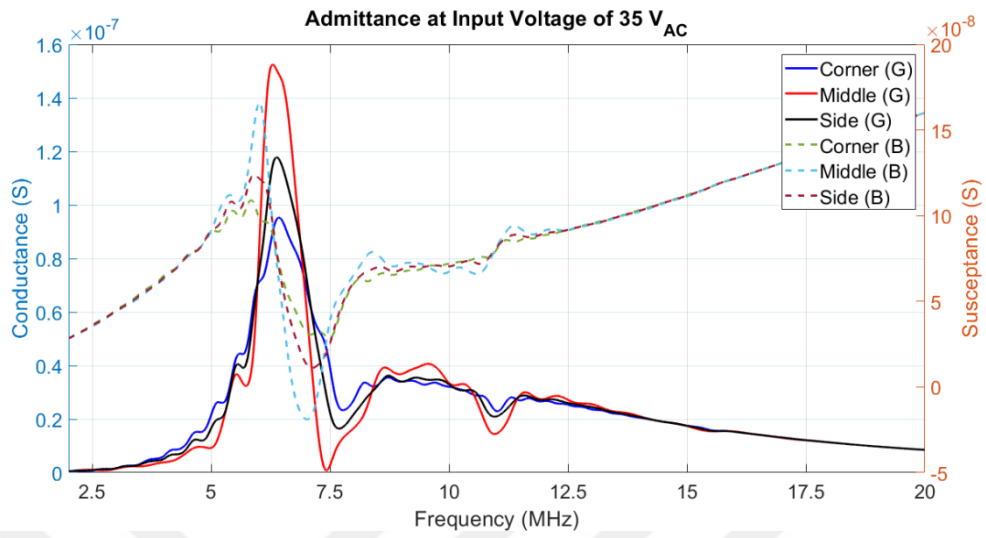


Figure B.2: Admittance at 35 V_{ac} input voltage. Susceptance values are shown in dashed lines.

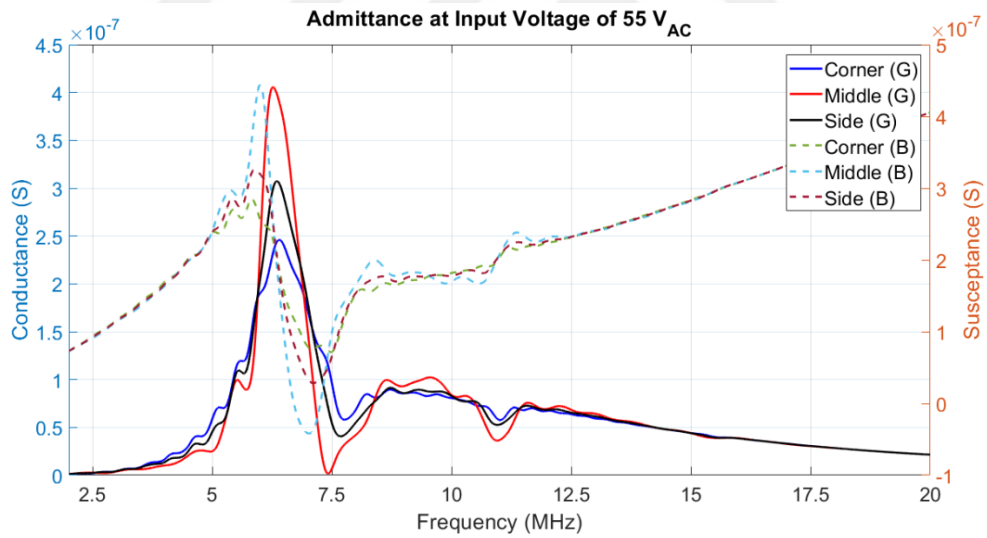


Figure B.3: Admittance at 55 V_{ac} input voltage. Susceptance values are shown in dashed lines.

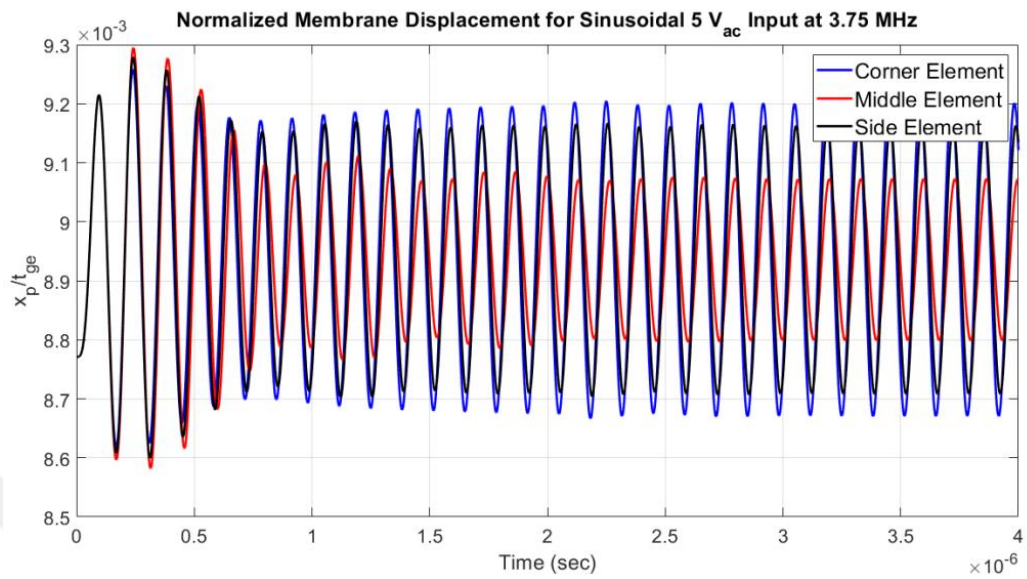


Figure B.4: Normalized membrane displacement for 5 volt transient sinusoidal input signal at 3.75 MHz.

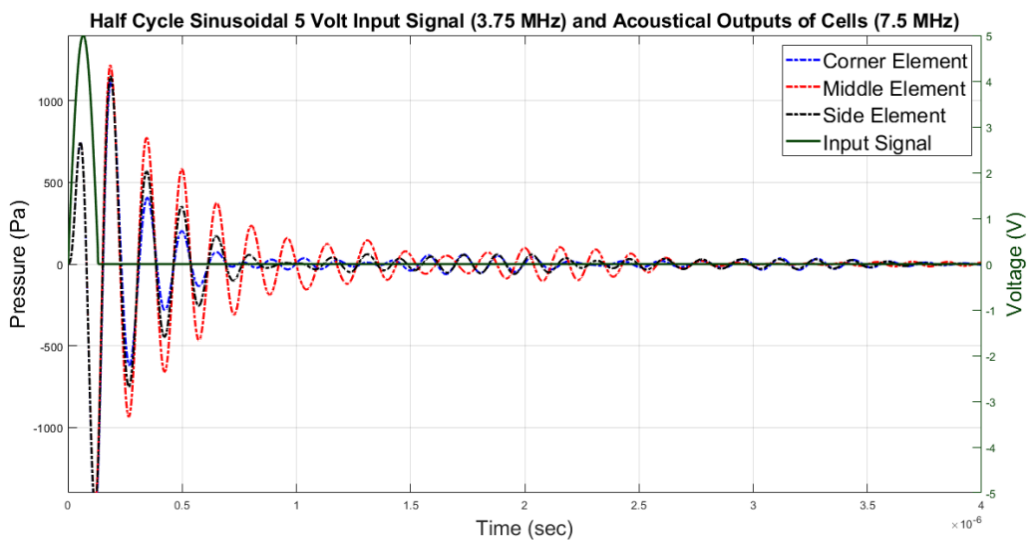


Figure B.5: Transient analysis at 3.75 MHz input frequency and input voltage level of 5 volts with half cycle sinusoidal waveforms.

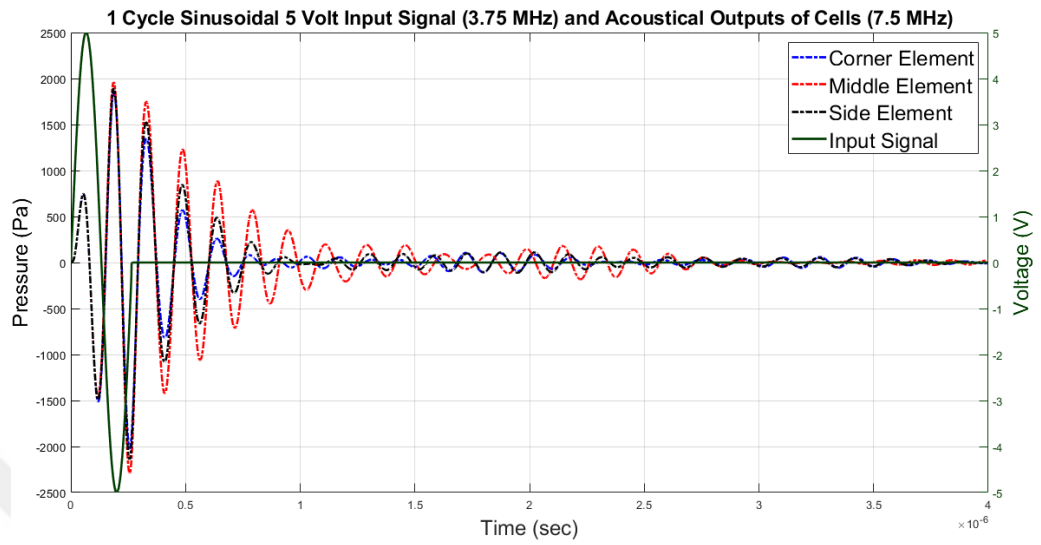


Figure B.6: Transient analysis at 3.75 MHz input frequency and input voltage level of 5 volts with one cycle sinusoidal waveforms.

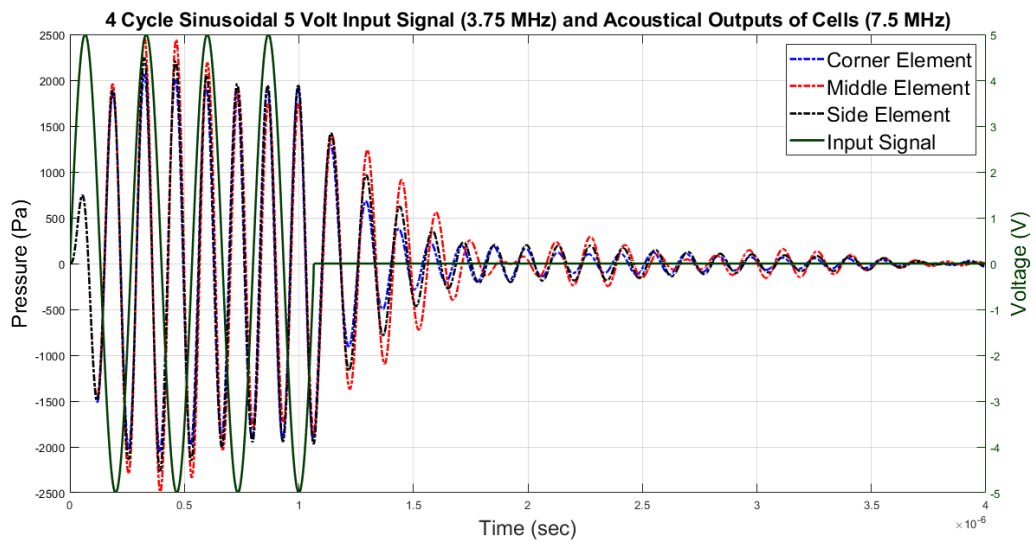


Figure B.7: Transient analysis at 3.75 MHz input frequency and input voltage level of 5 volts with four cycle sinusoidal waveforms.

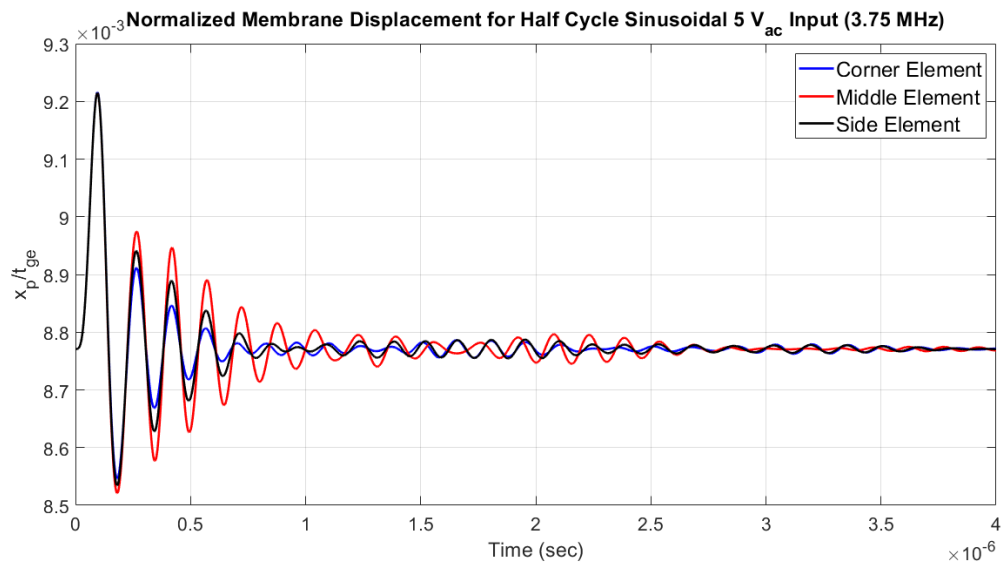


Figure B.8: Normalized membrane displacement for 5 volt half cycle sinusoidal input signal at 3.75 MHz.

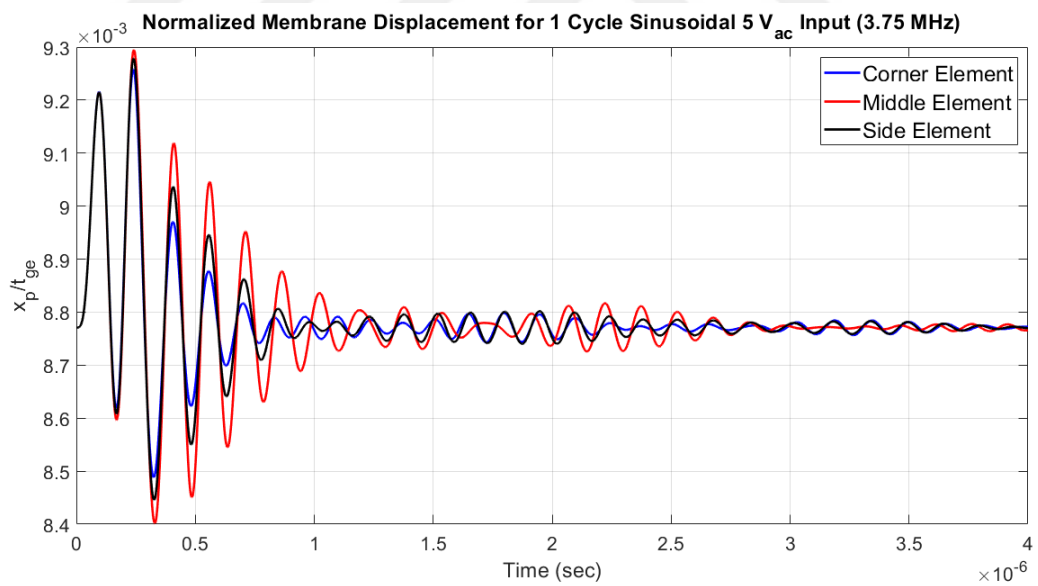


Figure B.9: Normalized membrane displacement for 5 volt 1 cycle sinusoidal input signal at 3.75 MHz.

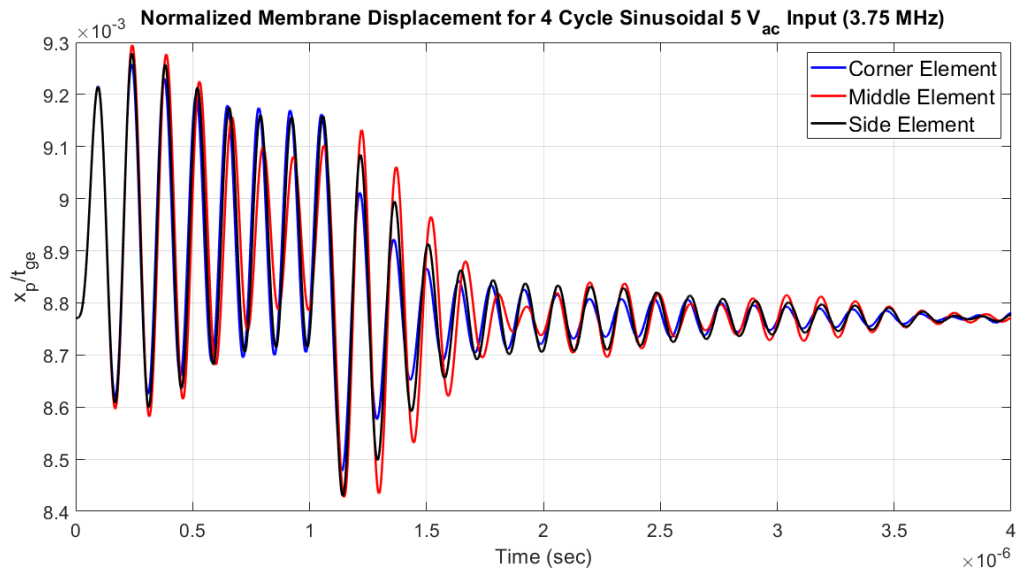


Figure B.10: Normalized membrane displacement for 5 volt 4 cycle sinusoidal input signal at 3.75 MHz.

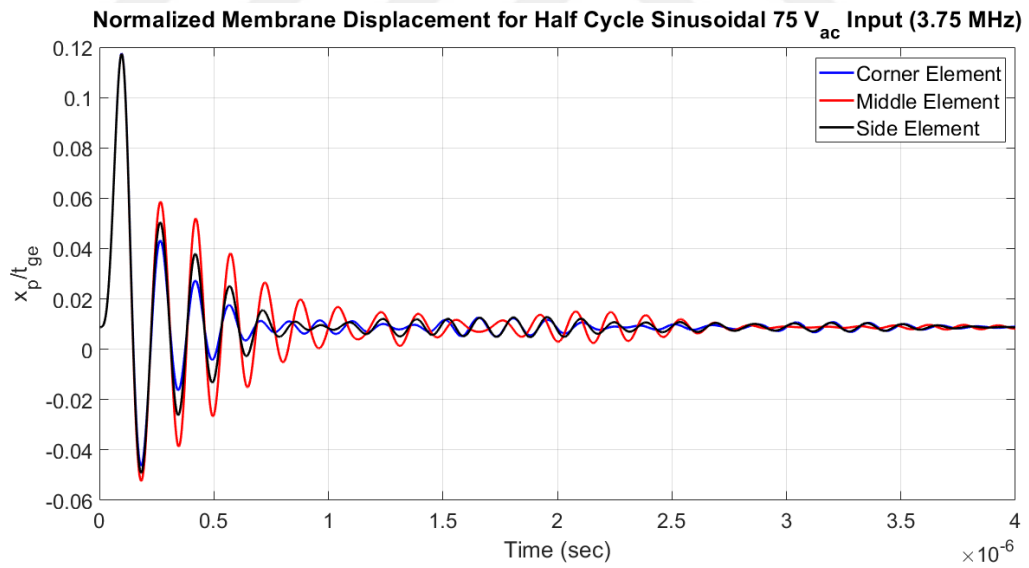


Figure B.11: Normalized membrane displacement for 75 volt half cycle sinusoidal input signal at 3.75 MHz.

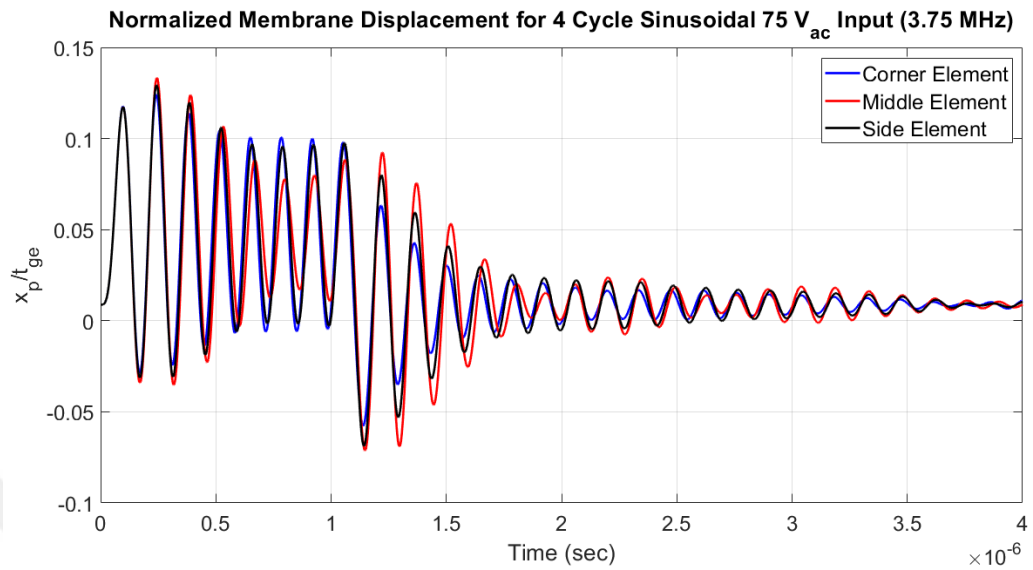


Figure B.12: Normalized membrane displacement for 75 volt 4 cycle sinusoidal input signal at 3.75 MHz.

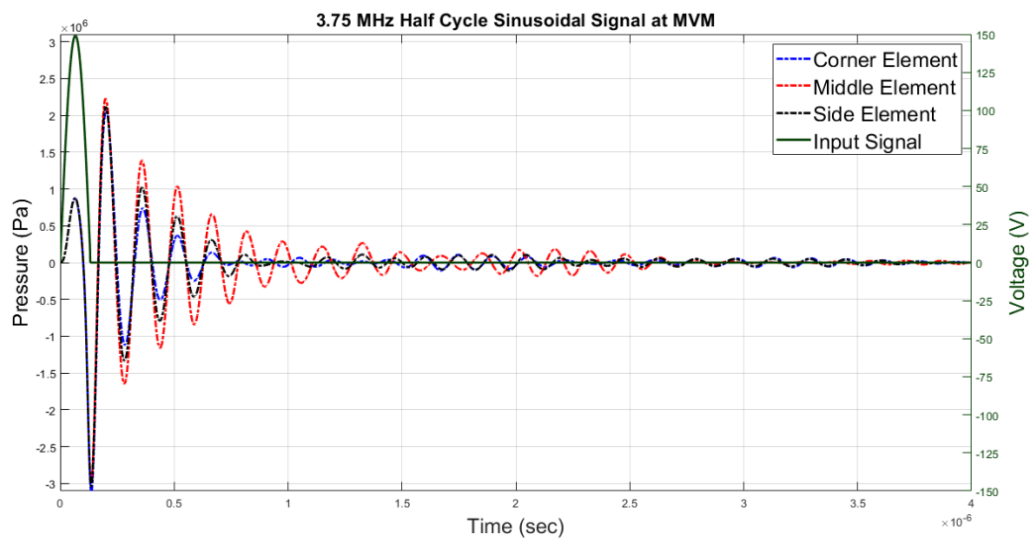


Figure B.13: Transient analysis at 3.75 MHz input frequency and input voltage level of 149.2 V_{ac} (MVM) with half cycle sinusoidal waveforms.

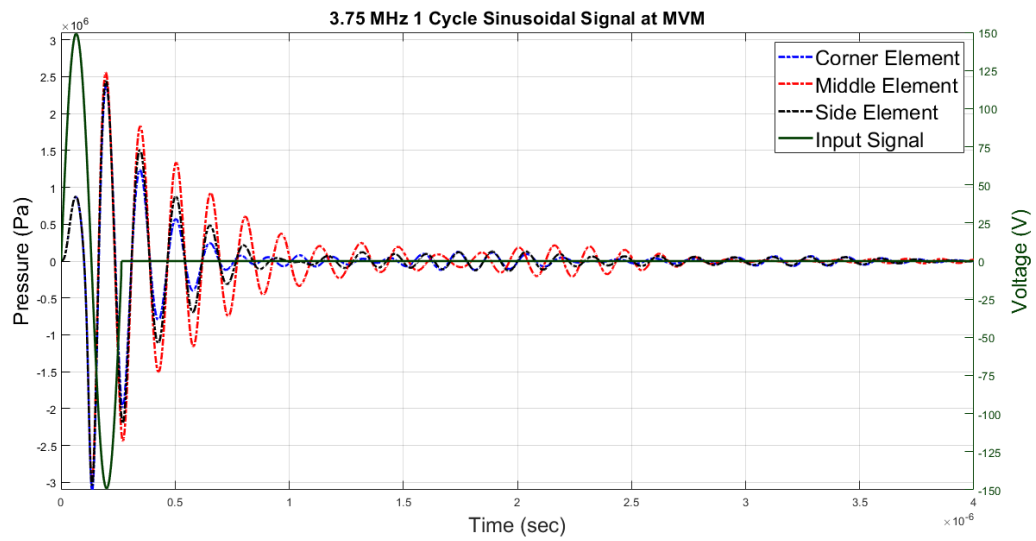


Figure B.14: Transient analysis at 3.75 MHz input frequency and input voltage level of $149.2 V_{ac}$ (MVM) with 1 cycle sinusoidal waveforms.

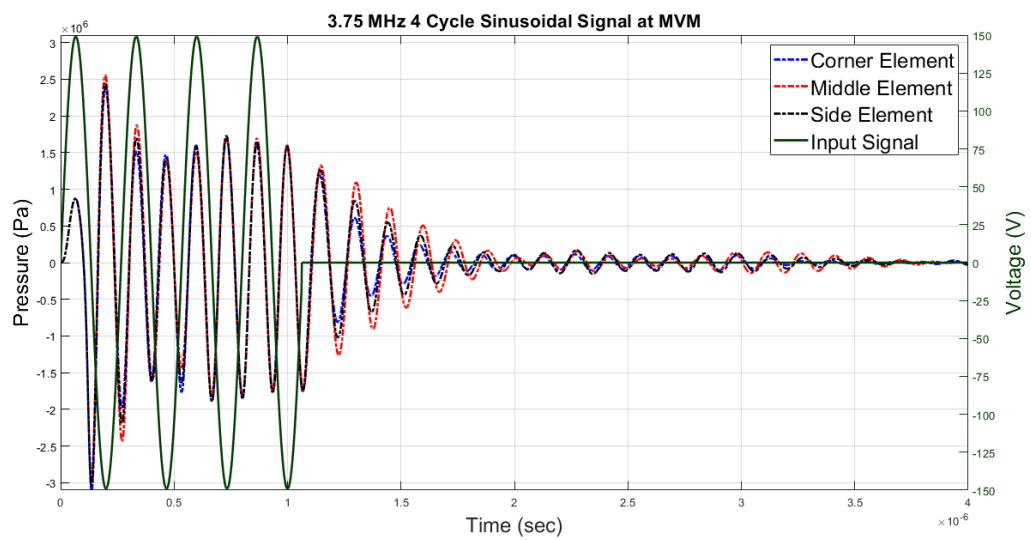


Figure B.15: Transient analysis at 3.75 MHz input frequency and input voltage level of $149.2 V_{ac}$ (MVM) with 4 cycle sinusoidal waveforms.

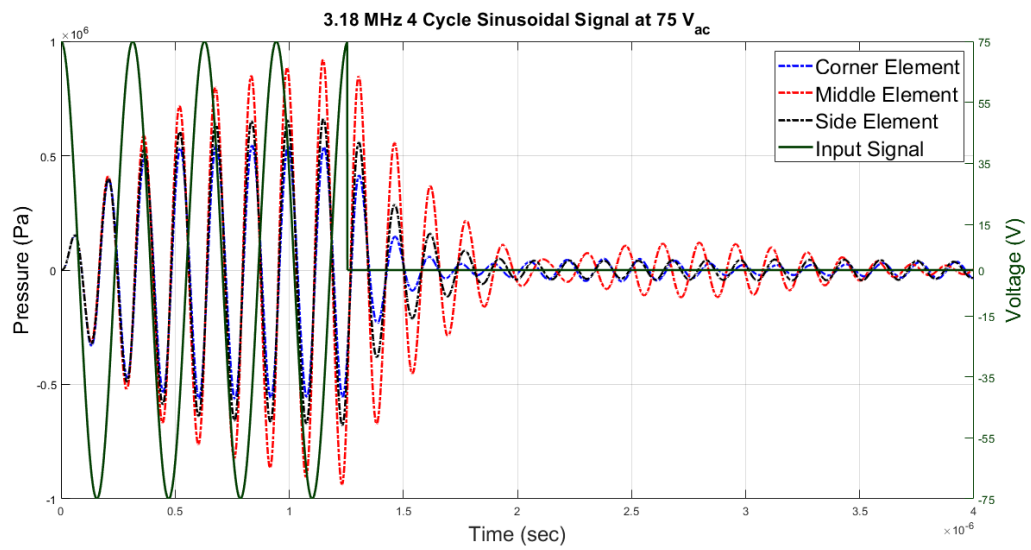


Figure B.16: Transient analysis at peak frequency of 3.18 MHz and input voltage level of 75 V_{ac} with 4 cycle sinusoidal waveforms.

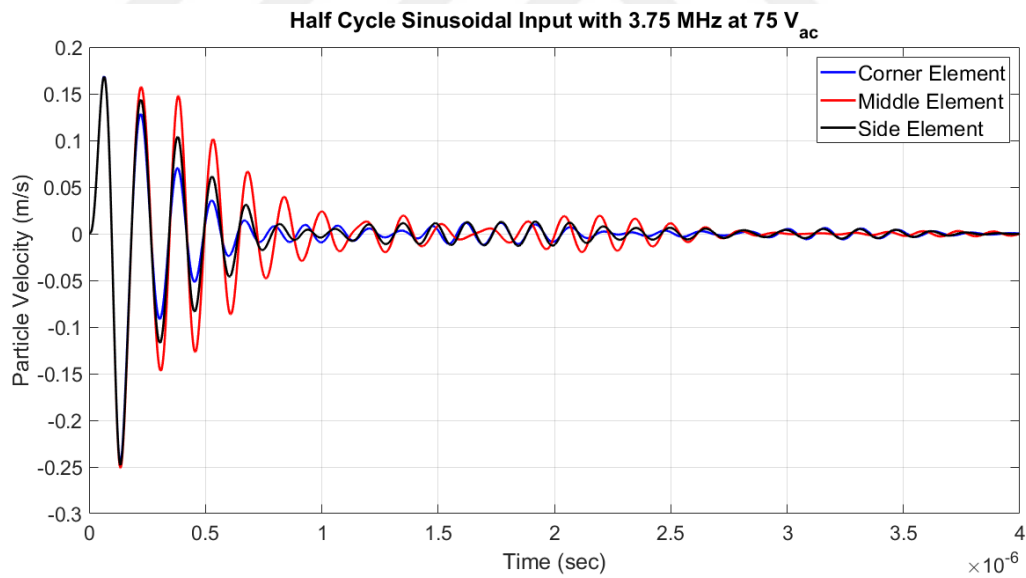


Figure B.17: Particle velocity obtained for half cycle sinusoidal input with operation frequency 3.75 MHz and 75 V_{ac}.

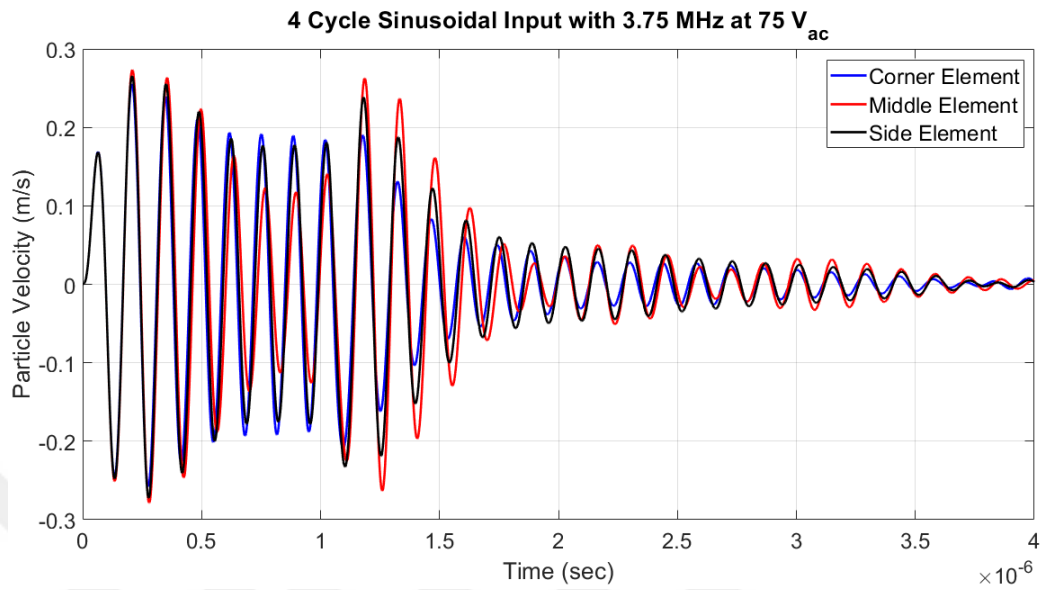


Figure B.18: Particle velocity obtained for 4 cycle sinusoidal input with operation frequency 3.75 MHz and 75 V_{ac}.

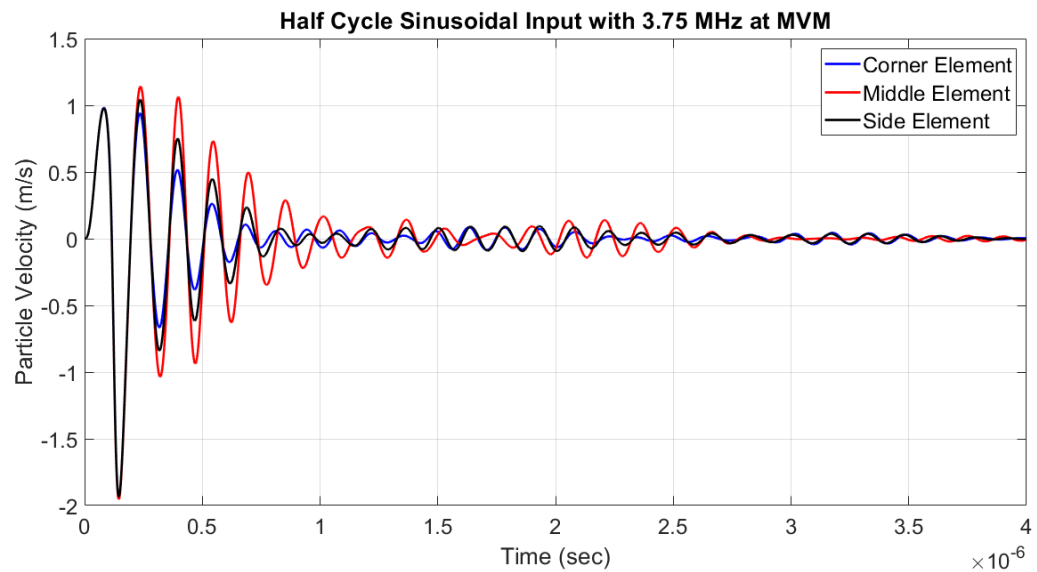


Figure B.19: Particle velocity obtained for half cycle sinusoidal input with operation frequency 3.75 MHz and 149.2 V_{ac} (MVM).

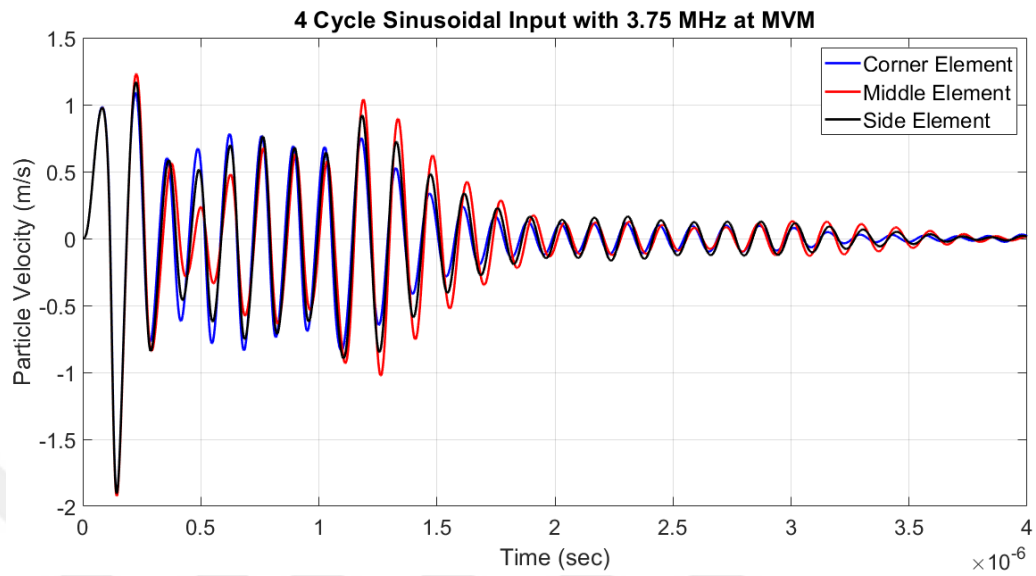


Figure B.20: Particle velocity obtained for 4 cycle sinusoidal input with operation frequency 3.75 MHz and 149.2 V_{ac} (MVM).

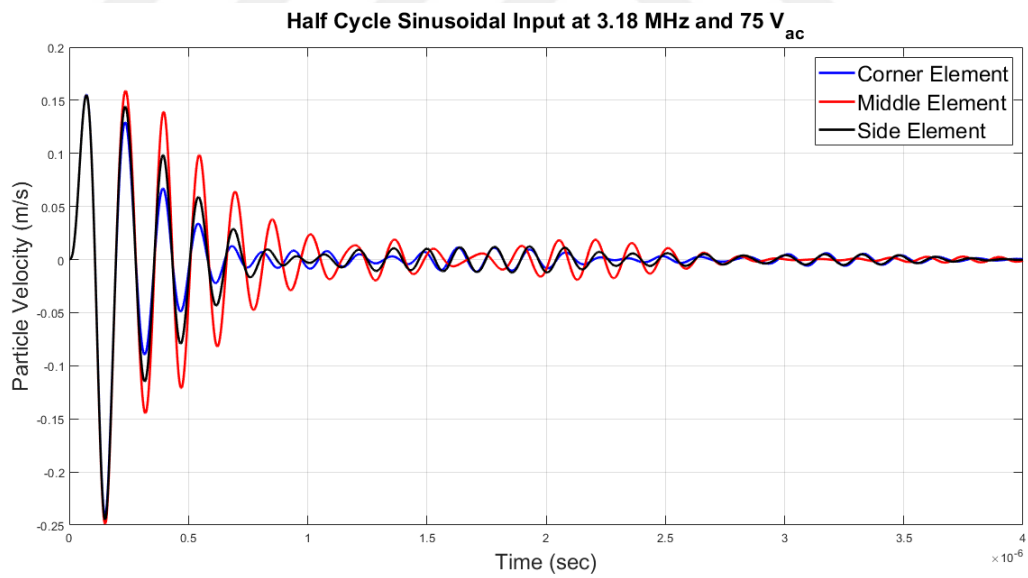


Figure B.21: Particle velocity obtained for half cycle sinusoidal input with peak frequency 3.18 MHz and 75 V_{ac} .

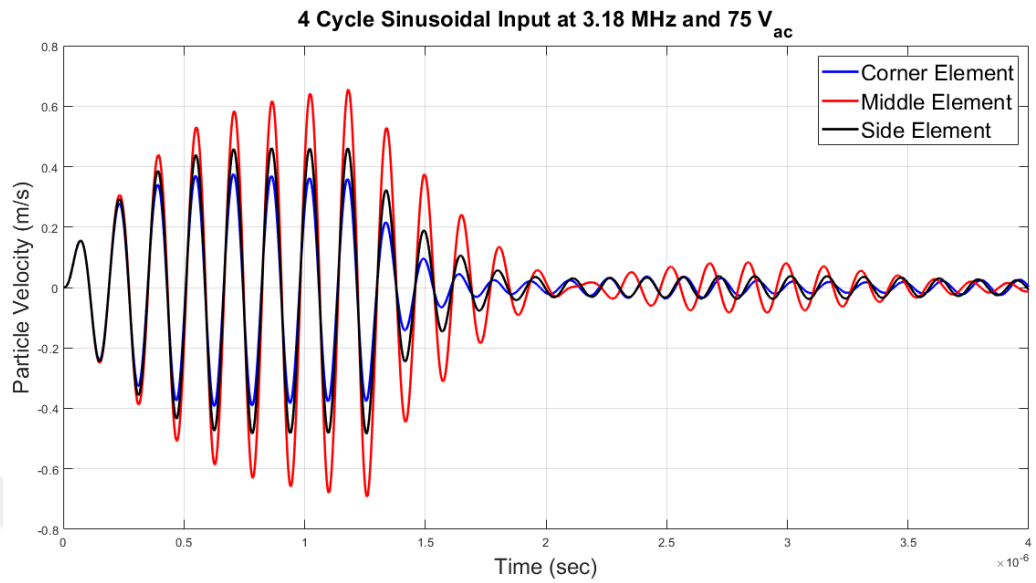


Figure B.22: Particle velocity obtained for 4 cycle sinusoidal input with peak frequency 3.18 MHz and 75 V_{ac} .

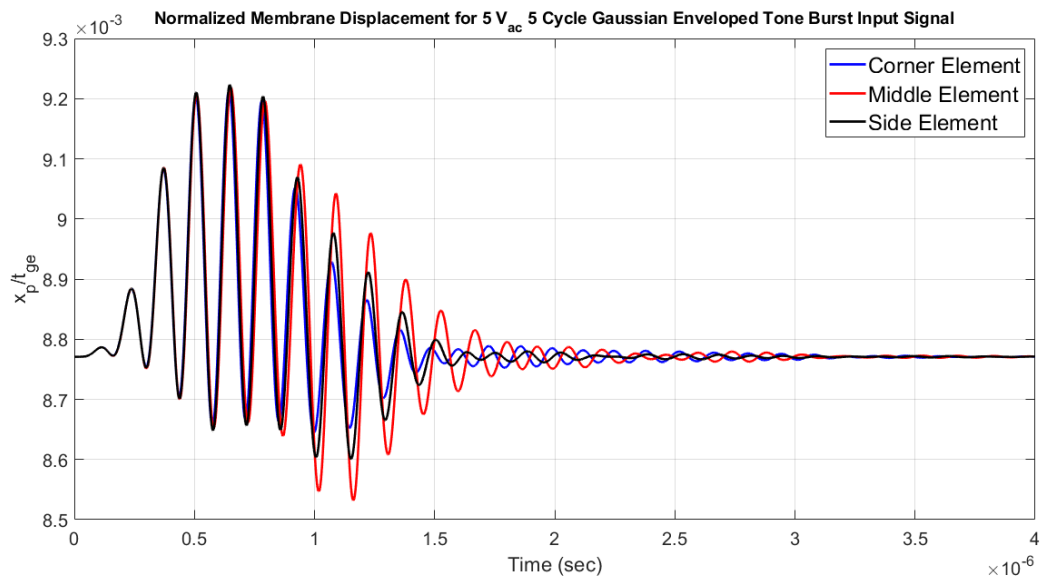


Figure B.23: Normalized membrane displacement for 5 cycle Gaussian enveloped tone burst signal at operation frequency of 3.75 MHz and 5 V_{ac} .

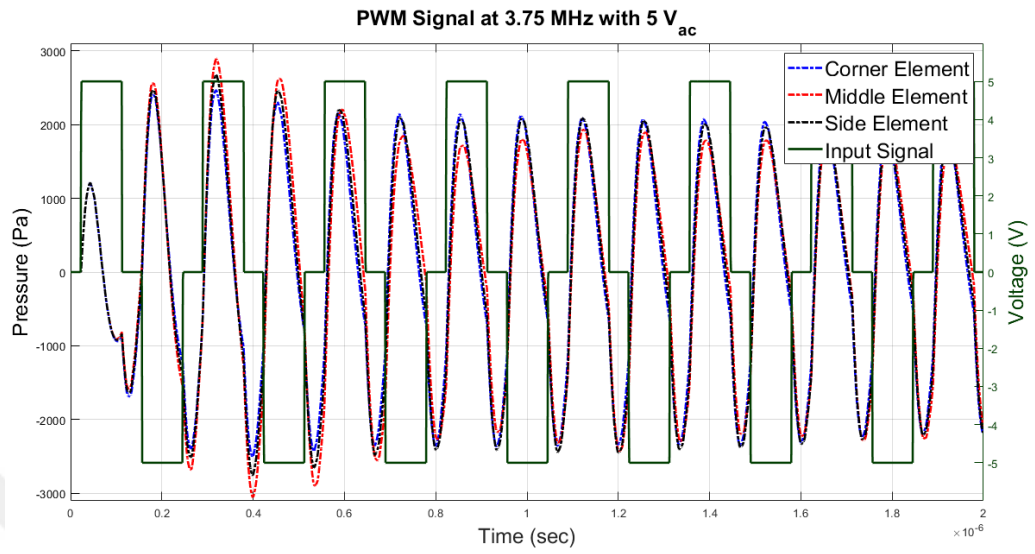


Figure B.24: Transient analysis at operation frequency of 3.75 MHz and input voltage level of 5 V_{ac} with transient PWM waveforms.

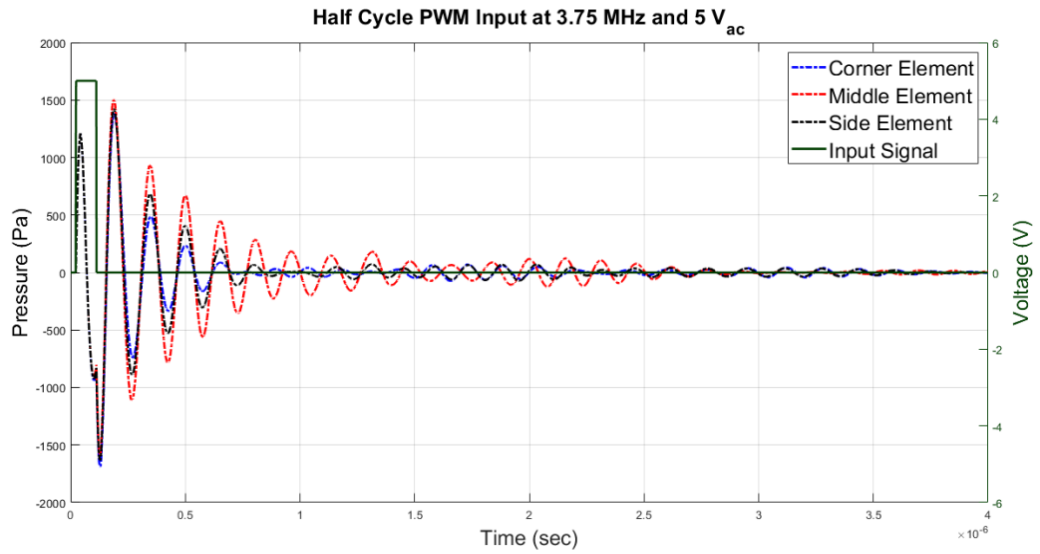


Figure B.25: Transient analysis at operation frequency of 3.75 MHz and input voltage level of 5 V_{ac} with half cycle PWM waveforms.

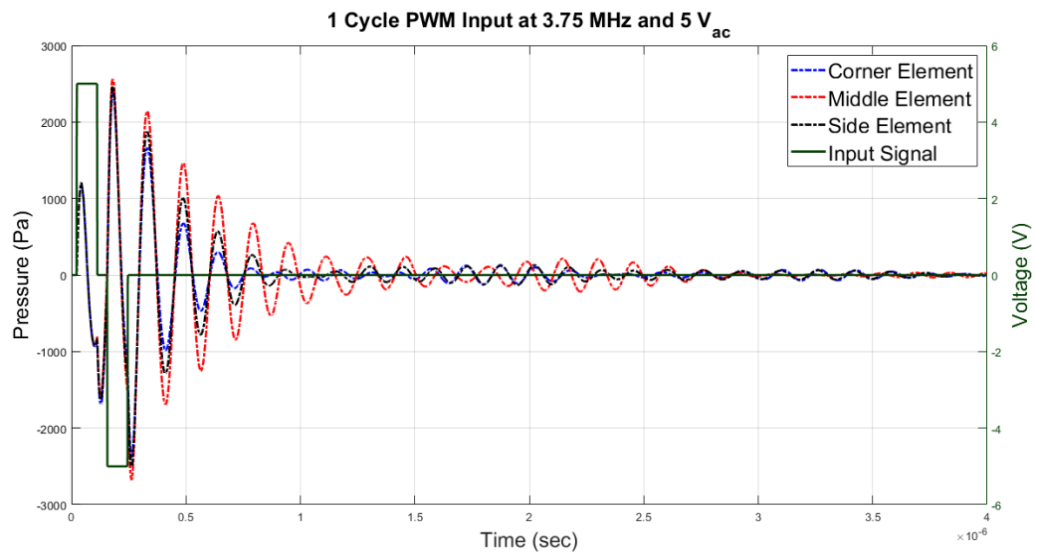


Figure B.26: Transient analysis at operation frequency of 3.75 MHz and input voltage level of 5 V_{ac} with 1 cycle PWM waveforms.

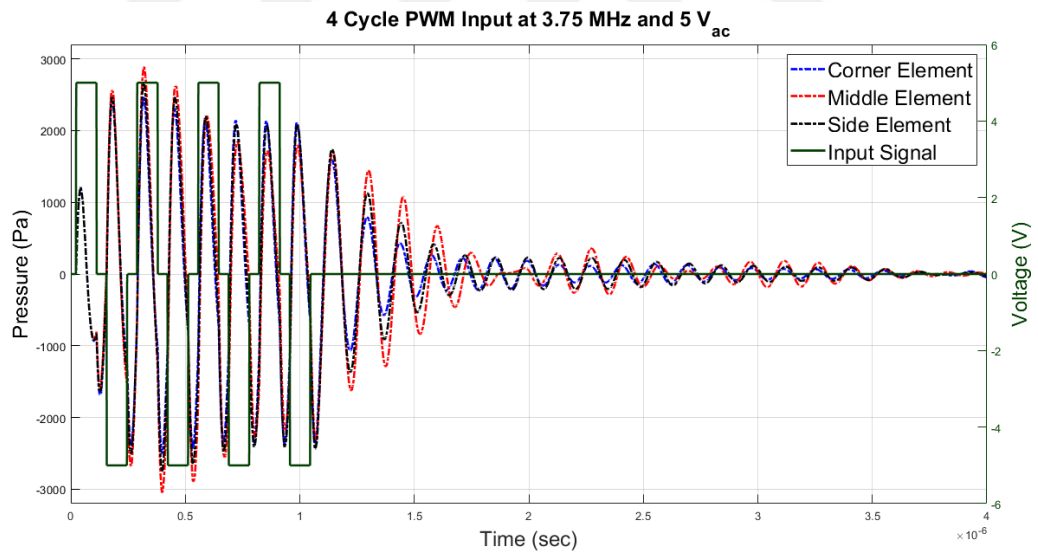


Figure B.27: Transient analysis at operation frequency of 3.75 MHz and input voltage level of 5 V_{ac} with 4 cycle PWM waveforms.

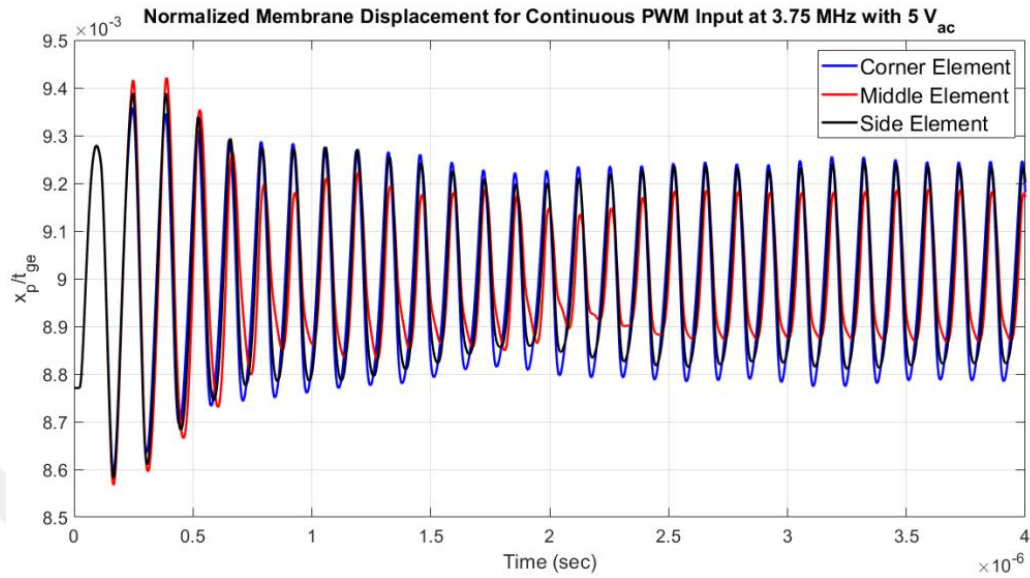


Figure B.28: Normalized membrane displacement for operation frequency of 3.75 MHz and input voltage level of 5 V_{ac} with transient PWM waveforms.

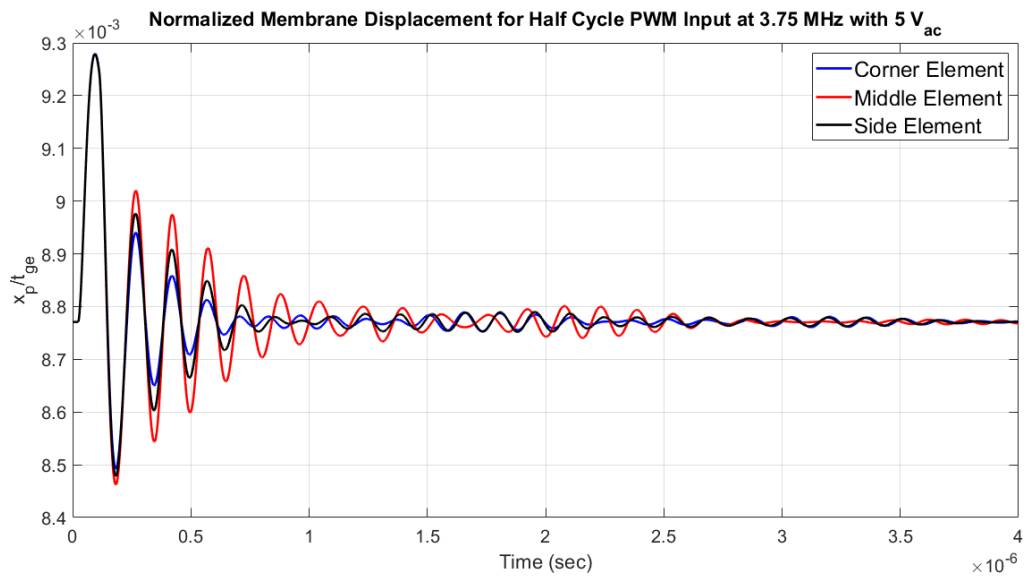


Figure B.29: Normalized membrane displacement for operation frequency of 3.75 MHz and input voltage level of 5 V_{ac} with half cycle PWM waveforms.

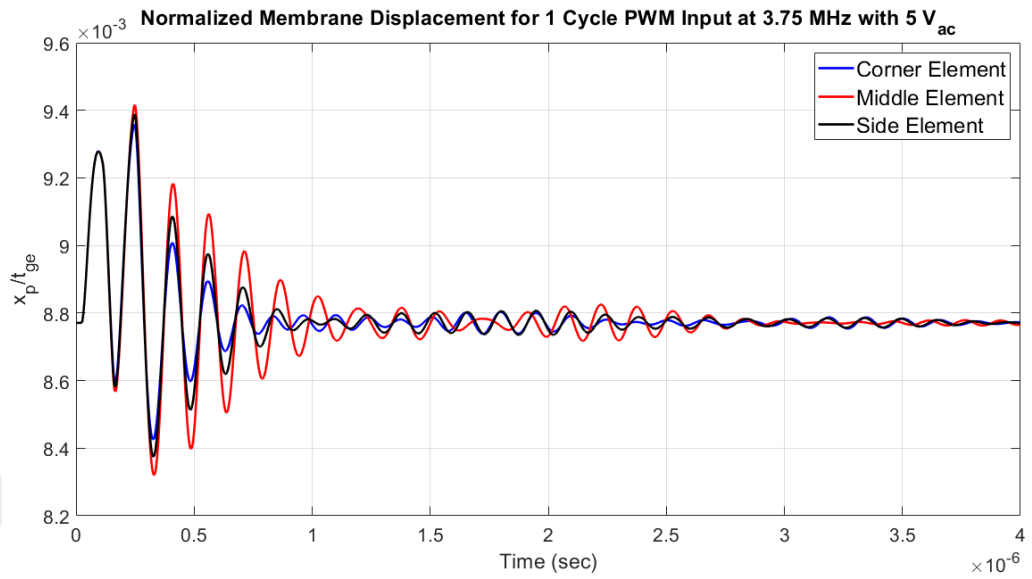


Figure B.30: Normalized membrane displacement for operation frequency of 3.75 MHz and input voltage level of 5 V_{ac} with 1 cycle PWM waveforms.

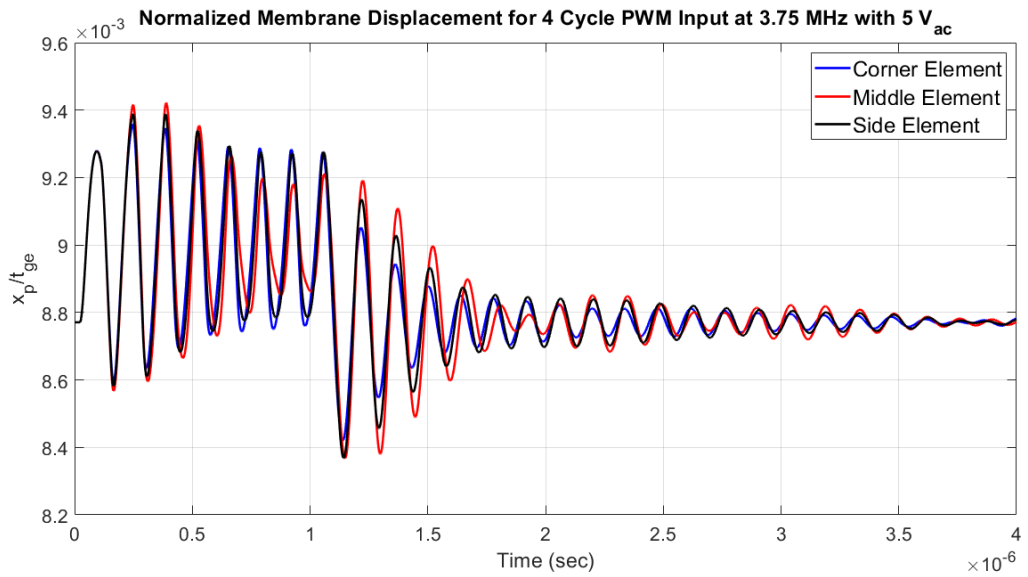


Figure B.31: Normalized membrane displacement for operation frequency of 3.75 MHz and input voltage level of 5 V_{ac} with 4 cycle PWM waveforms.

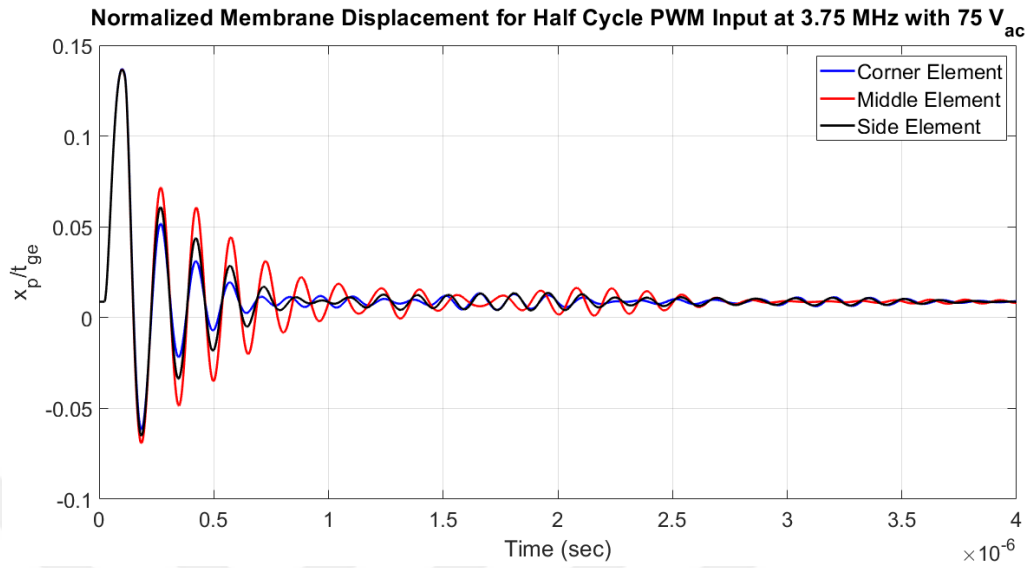


Figure B.32: Normalized membrane displacement for operation frequency of 3.75 MHz and input voltage level of 75 V_{ac} with half cycle PWM waveforms.

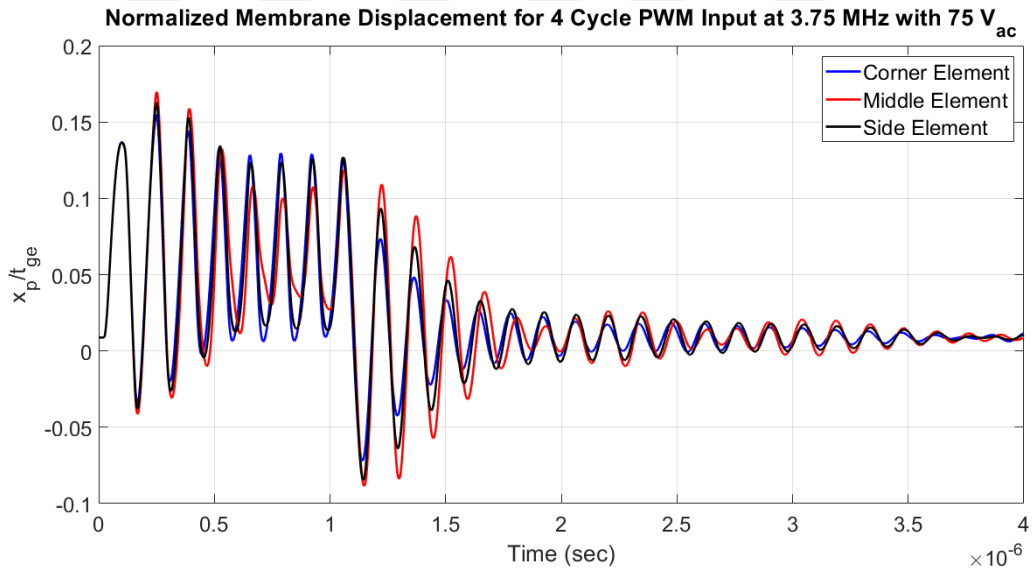


Figure B.33: Normalized membrane displacement for operation frequency of 3.75 MHz and input voltage level of 75 V_{ac} with 4 cycle PWM waveforms.

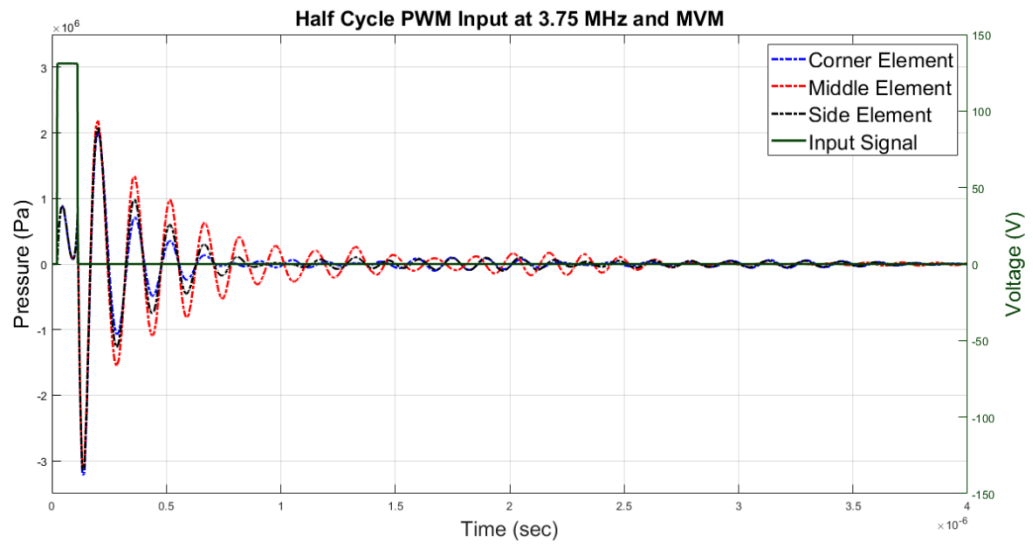


Figure B.34: Transient analysis at operation frequency of 3.75 MHz and input voltage level of 131 V_{ac} (MVM) with half cycle PWM waveforms.

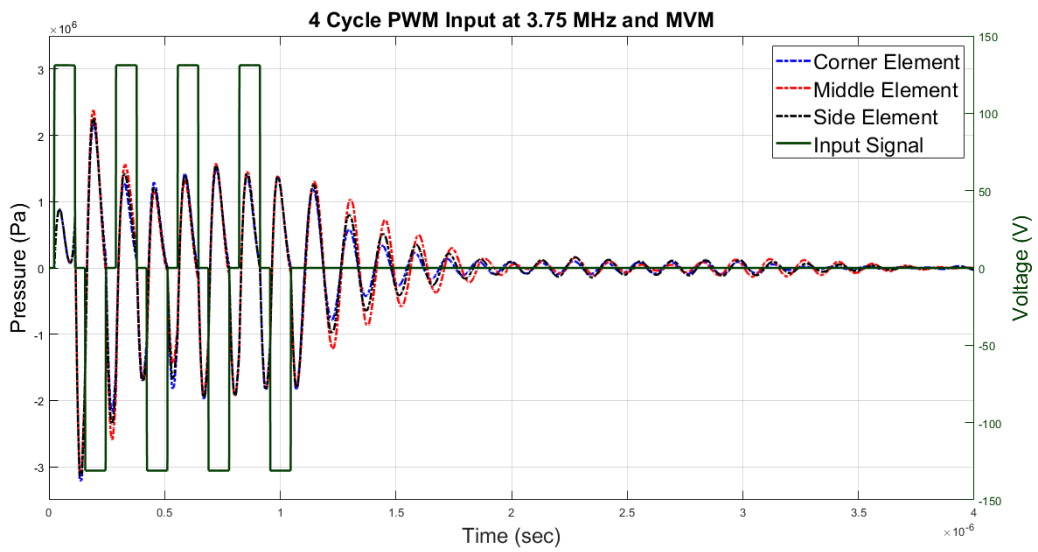


Figure B.35: Transient analysis at operation frequency of 3.75 MHz and input voltage level of 131 V_{ac} (MVM) with 4 cycle PWM waveforms.

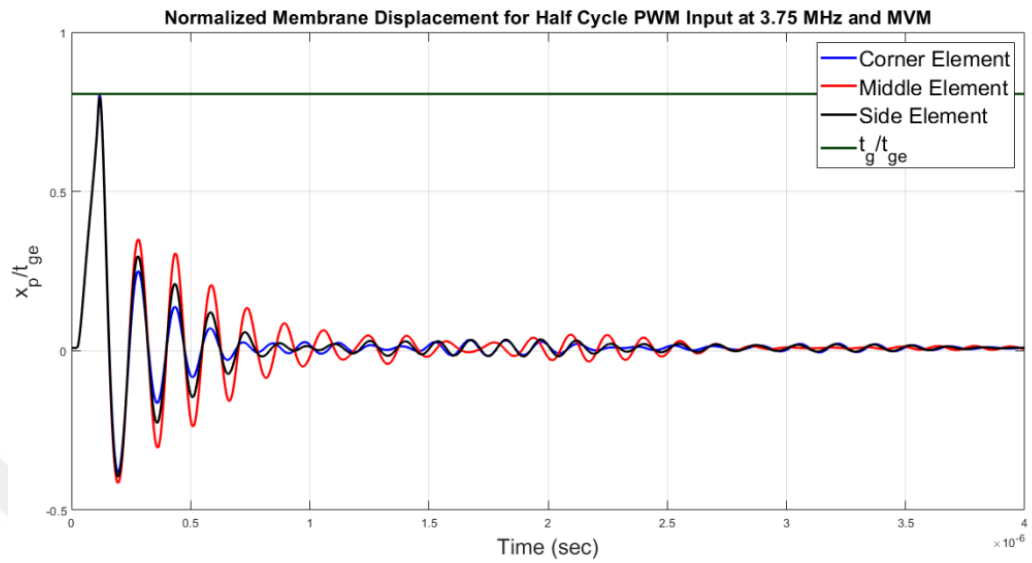


Figure B.36: Normalized membrane displacement for operation frequency of 3.75 MHz and input voltage level of 131 V_{ac} (MVM) with half cycle PWM waveforms.

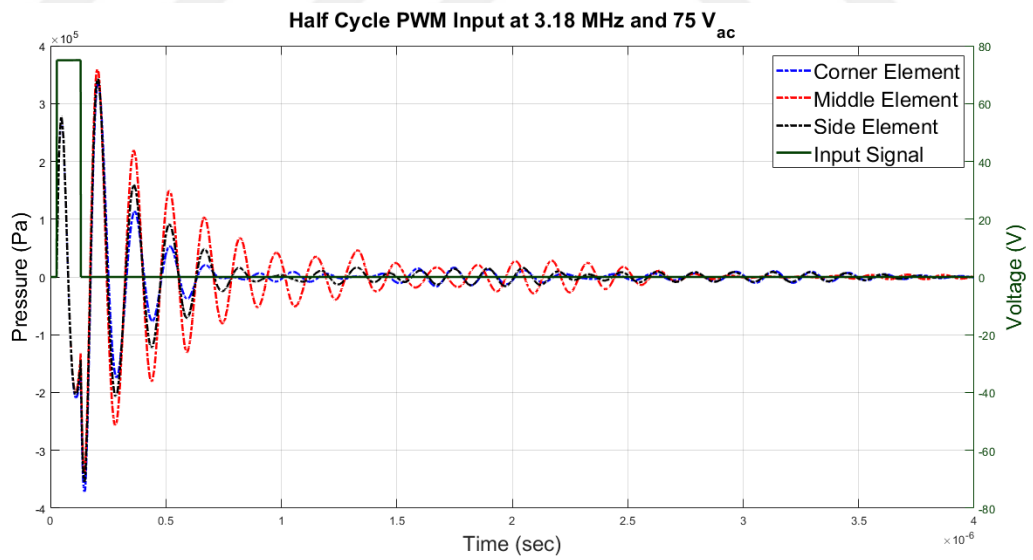


Figure B.37: Transient analysis at peak frequency of 3.18 MHz and input voltage level of 75 V_{ac} with half cycle PWM waveforms.

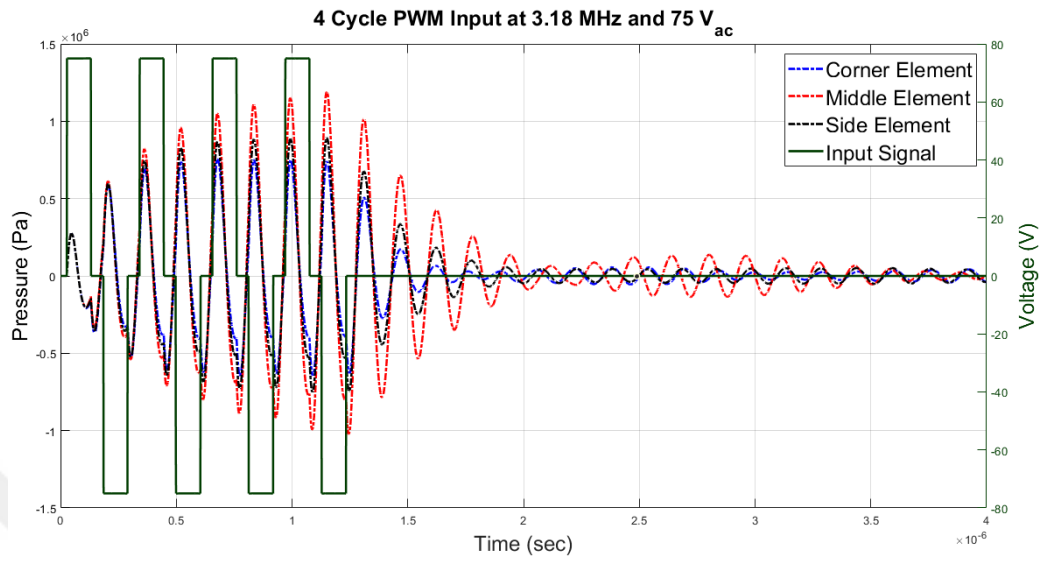


Figure B.38: Transient analysis at peak frequency of 3.18 MHz and input voltage level of 75 V_{ac} with 4 cycle PWM waveforms.

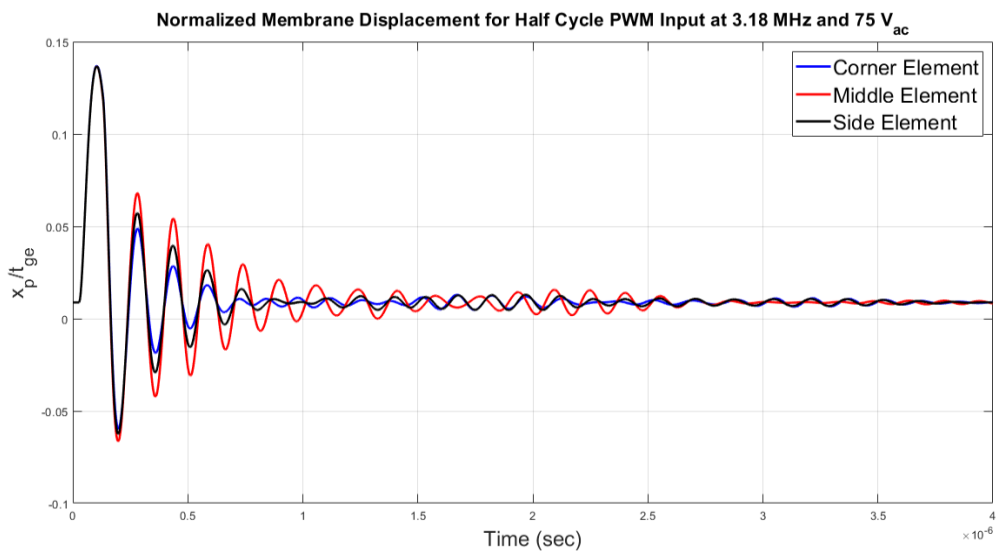


Figure B.39: Normalized membrane displacement at peak frequency of 3.18 MHz and input voltage level of 75 V_{ac} with half cycle PWM waveforms.

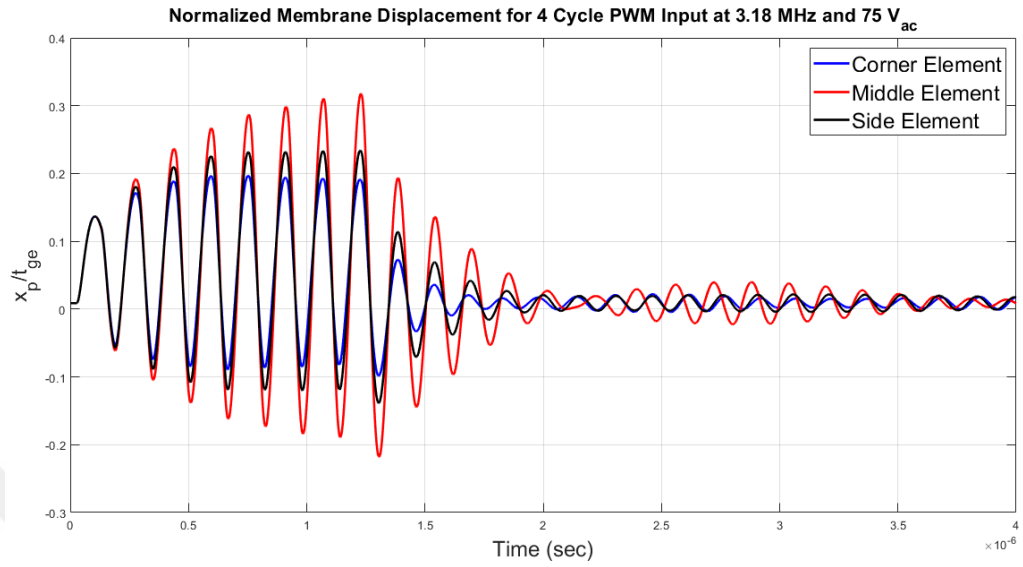


Figure B.40: Normalized membrane displacement at peak frequency of 3.18 MHz and input voltage level of 75 V_{ac} with 4 cycle PWM waveforms.

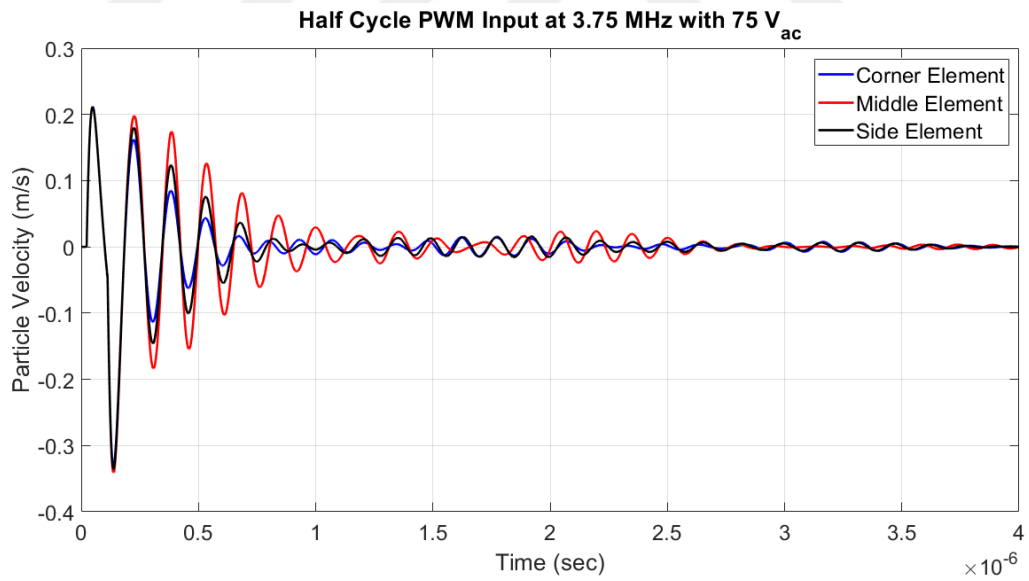


Figure B.41: Particle velocity observed at operation frequency of 3.75 MHz and input voltage level of 75 V_{ac} with half cycle PWM waveforms.

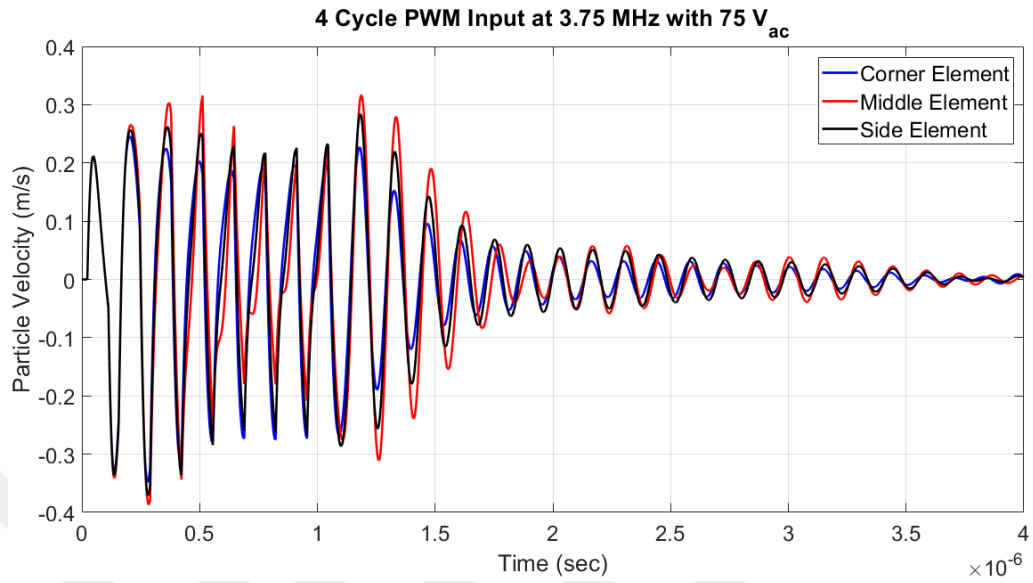


Figure B.42: Particle velocity observed at operation frequency of 3.75 MHz and input voltage level of 75 V_{ac} with 4 cycle PWM waveforms.

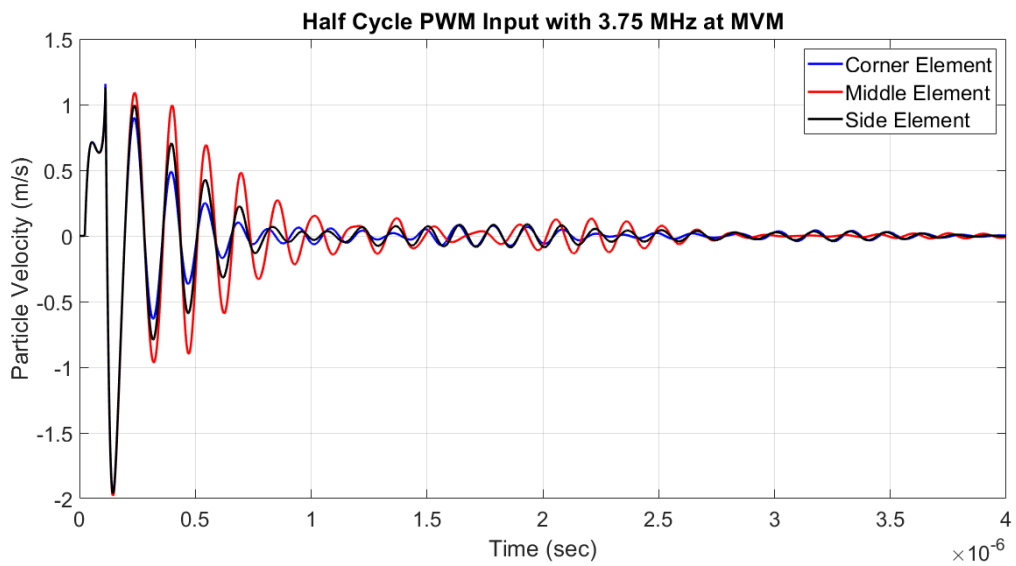


Figure B.43: Particle velocity observed at operation frequency of 3.75 MHz and input voltage level of 131 V_{ac} (MVM) with half cycle PWM waveforms.

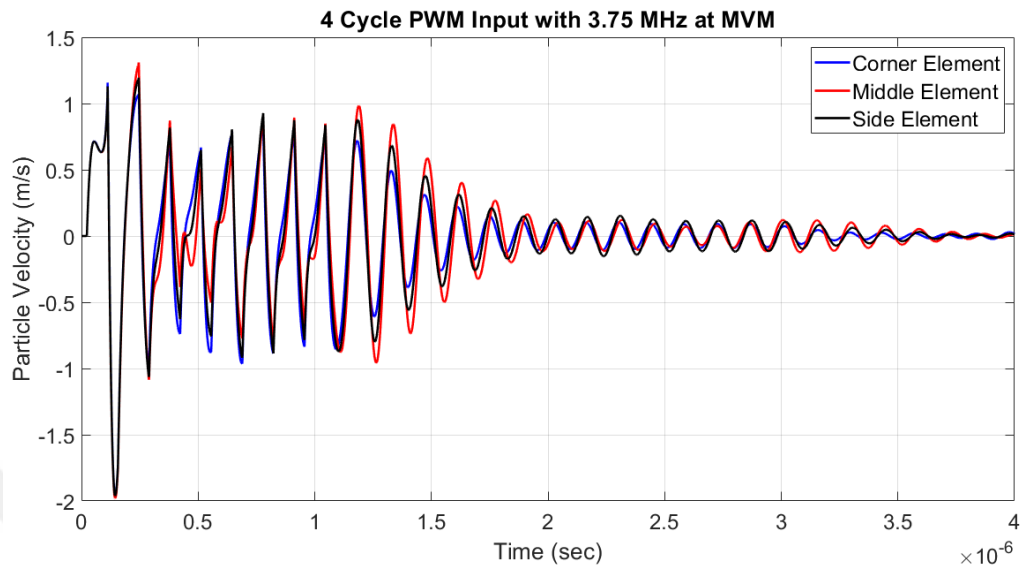


Figure B.44: Particle velocity observed at operation frequency of 3.75 MHz and input voltage level of $131 V_{ac}$ (MVM) with 4 cycle PWM waveforms.

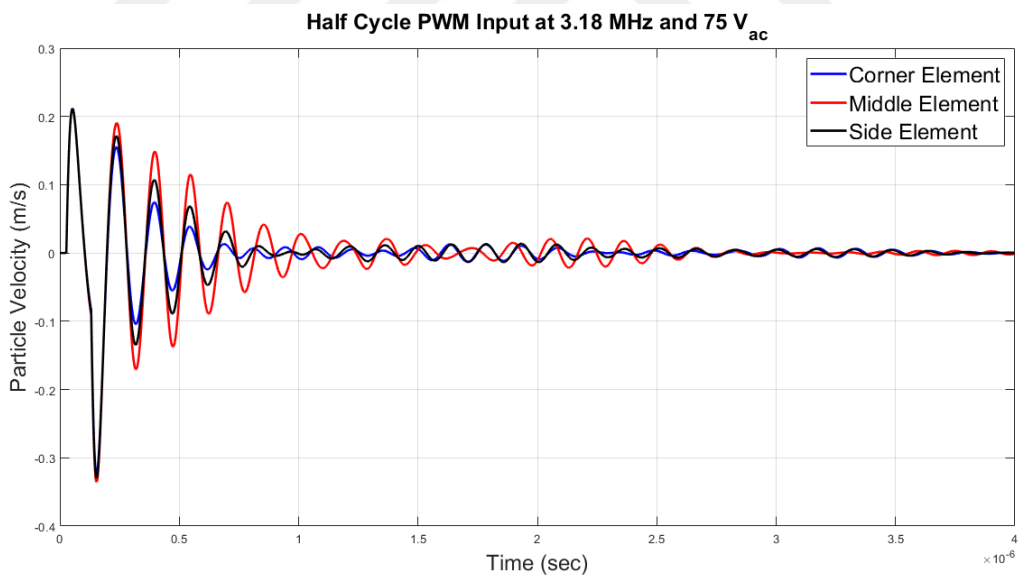


Figure B.45: Particle velocity observed at peak frequency of 3.18 MHz and input voltage level of $75 V_{ac}$ with half cycle PWM waveforms.

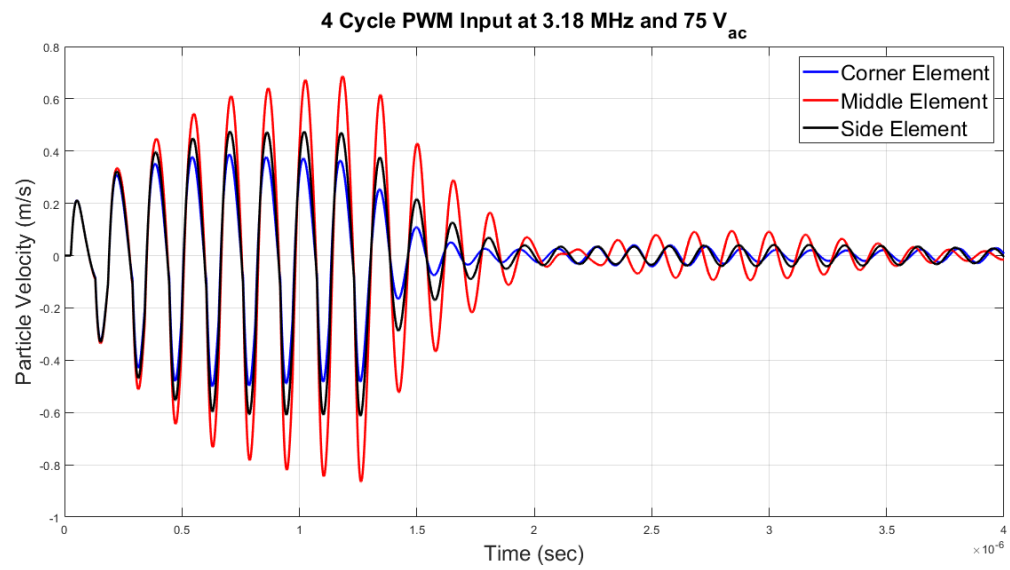


Figure B.46: Particle velocity observed at peak frequency of 3.18 MHz and input voltage level of 75 V_{ac} with 4 cycle PWM waveforms.

B.2 Extra Fabrication Graphics

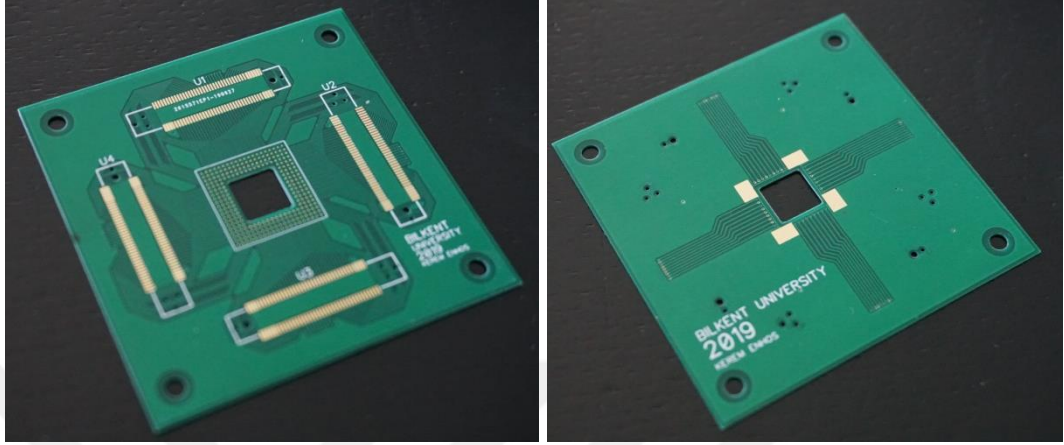


Figure B.47: Designed 0.4 mm PCB for flip-chip bonding and CMUT cell connection.



Figure B.48: Reference numbers and placement orientation for each device on Pyrex wafer.

According to these reference numbers, gap height values measured by stylus profilometer for each device is written in the following table.

Table B.1: Two different stylus profilometer measurements (M1 & M2) from two different locations of the same device are taken for each device on both wafers. Averages of these two measurements (AV) are also included.

Devices	Wafer 1			Wafer 2		
	M1 (nm)	M2 (nm)	AV (nm)	M1 (nm)	M2 (nm)	AV (nm)
1	259.6	266.1	262.85	171.8	173.3	172.55
2	260.8	253.1	256.95	147.3	149.2	148.25
3	259.3	261.9	260.6	178.8	196.5	187.65
4	244.6	255.8	250.2	160	151.4	155.7
5	237.2	225.8	231.5	94.6	92.9	93.75
6	234.3	225.9	230.1	102.5	101.9	102.2
7	241.9	241.4	241.65	83.4	95.9	89.65
8	263.8	260.2	262	185.6	171.5	178.55
9	239.2	258.7	248.95	161.6	141.2	151.4
10	225.8	228.3	227.05	115.7	88.1	101.9
11	216.7	217.7	217.2	89.9	79.1	84.5
12	237.4	243.3	240.35	113.1	102.2	107.65
13	259	255.3	257.15	137.9	157.6	147.75
14	259.9	266.3	263.1	140.5	160.4	150.45
15	235.6	237.7	236.65	118.5	119.3	118.9
16	232.3	219.5	225.9	120.7	100.5	110.6
17	229.2	234.5	231.85	113.3	116.9	115.1
18	271.9	259.4	265.65	168.3	163.5	165.9
19	269.7	259.6	264.65	156.5	149.7	153.1
20	260.3	240.2	250.25	150	153.4	151.7
21	254.5	252.4	253.45	155.8	169.2	162.5

B.3 Extra Measurement Graphics

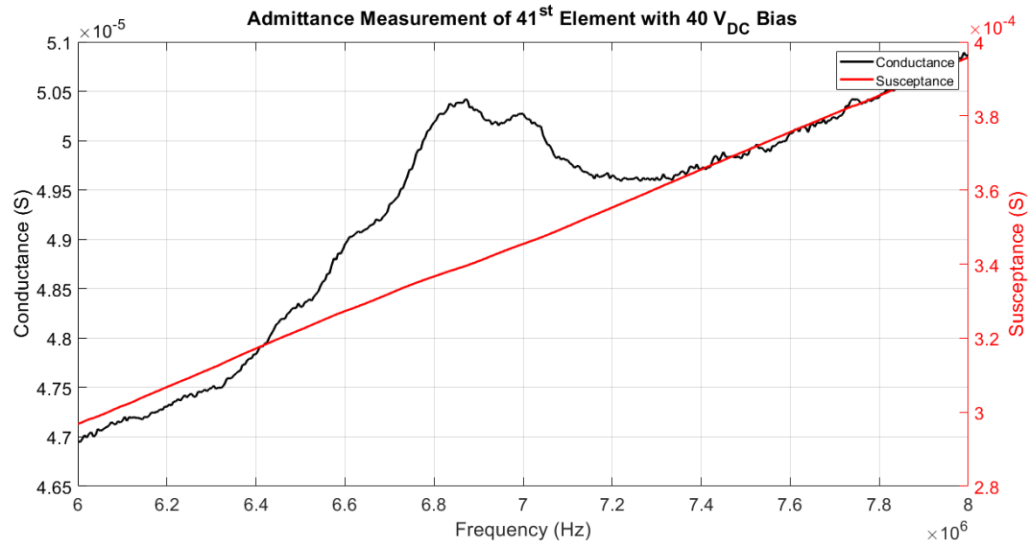


Figure B.49: Admittance of 41st element of the 7th device.

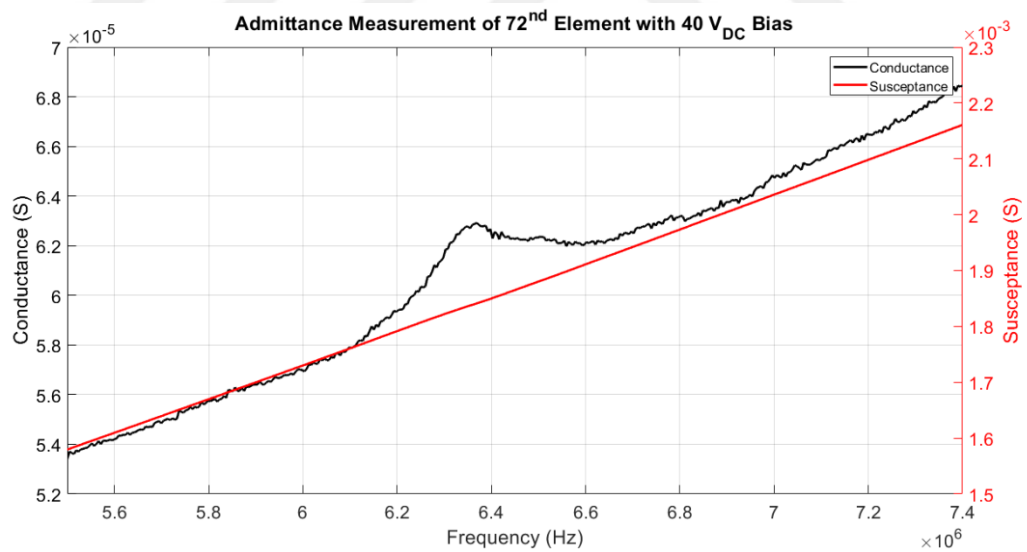


Figure B.50: Admittance of 72nd element of the 7th device.

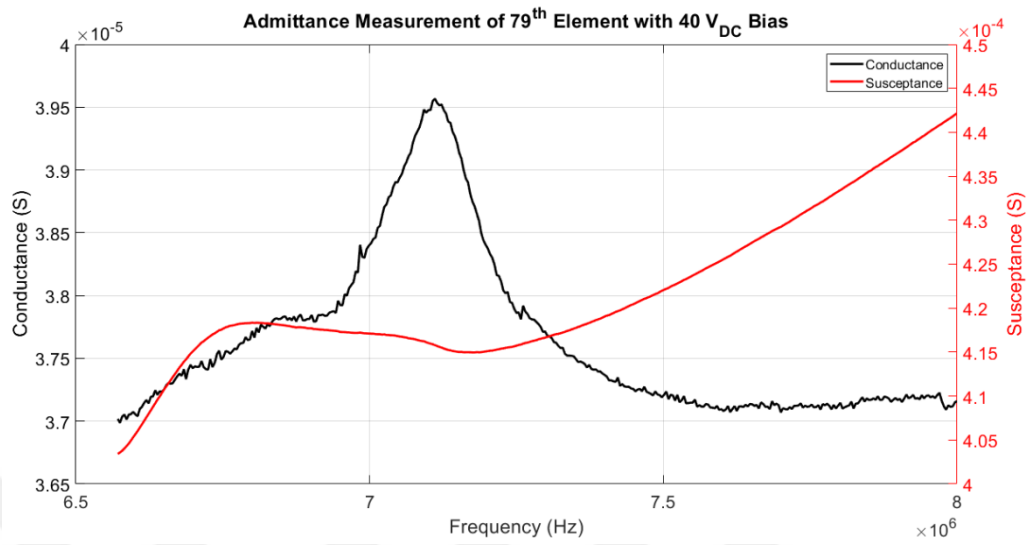


Figure B.51: Admittance of 79th element of the 7th device.

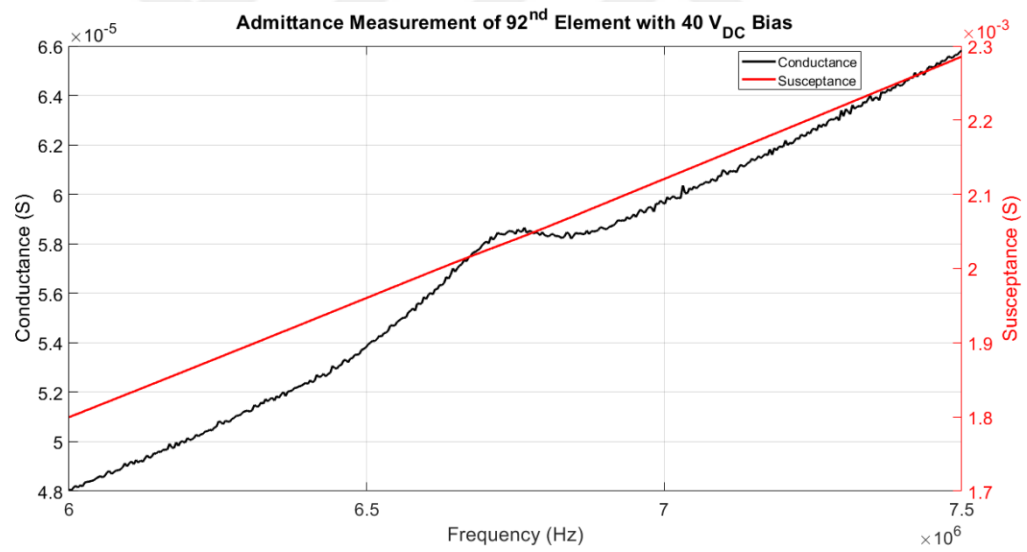


Figure B.52: Admittance of 92nd element of the 7th device.

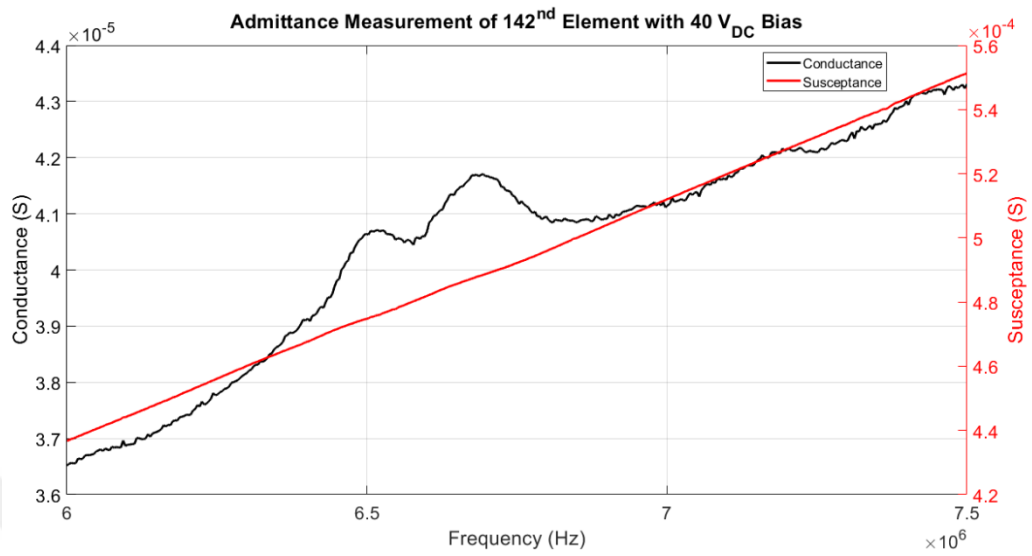


Figure B.53: Admittance of 142nd element of the 7th device.

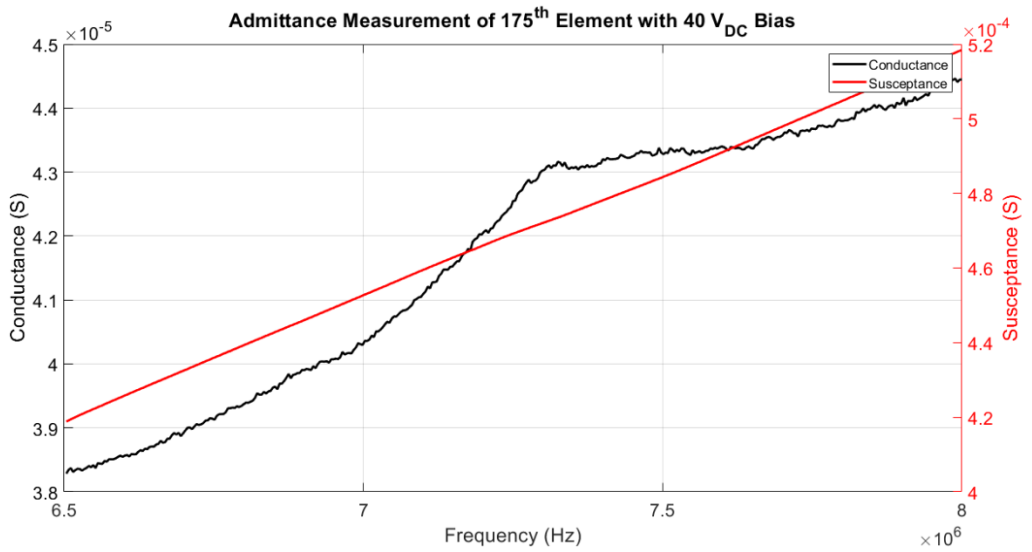


Figure B.54: Admittance of 175th element of the 7th device.

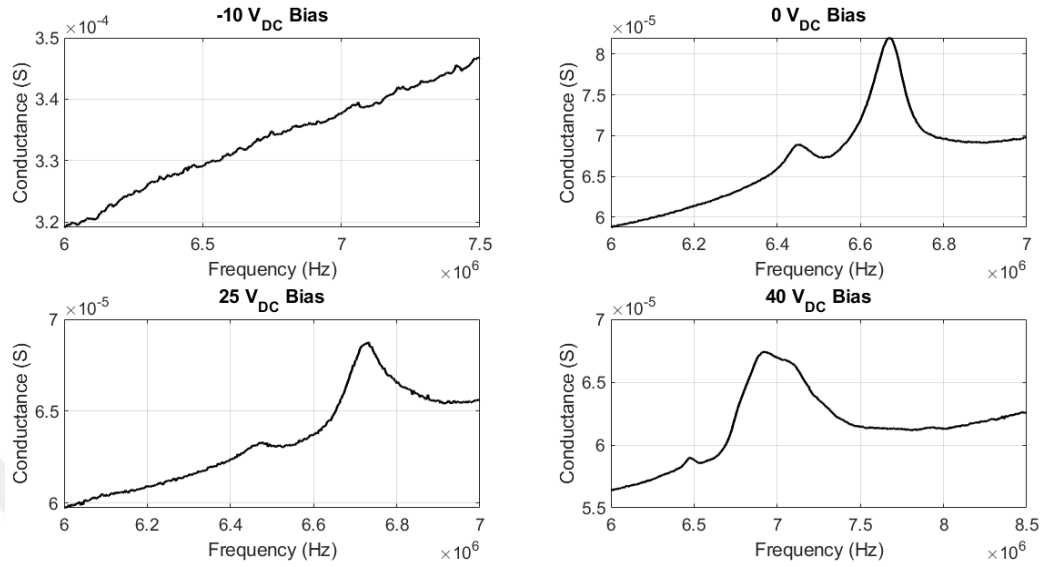


Figure B.55: Conductance of 156th element of the 7th device with different bias voltages. At -10 V_{DC} resonances are disappearing and at 0 V resonances can be observed, which indicates the charging of the fabricated devices.