Solid Micro Horn Array (SMIHA) for Acoustic Matching

S. Sherrit, X. Bao, Y. Bar-Cohen,

Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109, USA

ABSTRACT

Transduction of electrical signals to mechanical signals and vice-versa in piezoelectric materials is controlled by the material coupling coefficient. In general in a loss-less material the ratio of energy conversion per cycle is proportional to the square of the coupling coefficient. In practical transduction however the impedance mismatch between the piezoelectric material and the electrical drive circuitry or the mechanical structure can have a significant impact on the power transfer. This paper looks at novel methods of matching the acoustic impedance of structures to the piezoelectric material in an effort to increase power transmission and efficiency. In typical methods the density and acoustic velocity of the matching layer is adjusted to give good matching between the transducer and the load. The approach discussed in this paper utilizes solid micro horn arrays in the matching layer which channel the stress and increase the strain in the layer. This approach is found to have potential applications in energy harvesting, medical ultrasound and in liquid and gas coupled transducers.

KEYWORD: piezoelectric devices, acoustic wave, Acoustic matching, backing layers, impedance, power transmission.

1. INTRODUCTION

Piezoelectric transducers are used for emission and reception of ultrasonic signals in medical diagnosis and treatment, nondestructive evaluation, energy harvesting, active structural damping, and many other applications. In this paper a novel method of producing highly efficient ultrasound transducer using impedance matching layers that consist of an array of micro-horns sandwiched between two layers is presented. This design combines the use of horns that are used in high power ultrasonics to enhance the displacement of a surface and micromachining to produce highly efficient ultrasound transducers that can be tailored to match a wide variety of acoustic loads. For example, in medical ultrasound the acoustic impedance of the transducer is approximately 20-25 times greater than the acoustic impedance of human tissue and therefore the pressure transmission coefficient is only about 8 percent. The use of a matching layer is one of the most critical points in the proper design and manufacturing of ultrasonic transducers. The approach we allows for the design and manufacturing of matching layers that can be produced by variety of proven industrial processes using well defined materials with known mechanical properties. Prior techniques to increase the acoustic transmission include the use of ¼ wave matching layers [1], [2], graded layers [3] composite material matching layers [4], and piezoelectric/polymer composites [5], [6].

This paper describes a novel impedance matching layer approach that is based on an array of micro-horns sandwiched between two plates. These horns can be of a variety of cross sections and tapers including (stepped, linear, exponential, parabolic, Fourier etc) and of the order of 10's to 100's of microns long. They can be laid out in a two dimensional array (regular or randomized) and are connected between two plates which of the order of 10's of microns thick. This sandwich structure is then bonded to a piezoelectric transducer. The theoretical models suggest that by tailoring the various features (e.g. cross sectional area profile, length , plate thickness and material choice for the horns, back plate and face plate) of the horn one can produce transducers with near perfect matching to the acoustic load and power transmission efficiencies of 90% or greater with very large

bandwidths. Other features of these matching layers are that their design is amenable to MEMS fabrication, Silicon integration and micromaching, tape casting, laser micro-machining and multilayer co-fired fabrication techniques. They may also be integrated into 1D and 2D array transducers. By adjusting the horn distribution density one may also be able to pulse shape the acoustic signal (eg. Gaussian rather than Piston) to produce a desired pulse shape. These Solid MicroHorn Array (SMiHA) designs can be used to enhance the performance of ultrasonic transducers that are used for NDE of spacecraft structures providing a very high resolution taking advantage of the large emitted and received bandwidth. In addition these matching layers can be used for active structural damping or energy harvesting applications in future NASA missions. This matching layer approach may also be beneficial in high frequency medical ultrasound.

2. BACKGROUND

In order to transmit and receive acoustic waves through various materials and assure minimum loses to reflections at the interface it is necessary to match the acoustic impedance of the materials that are encountered along the path of the wave. Most of the current high frequency ultrasound transducers that are used for medical and NDE applications are based on piezoelectric materials and PZT (Lead Zirconate Titanate) in particular. For PZT the acoustic velocity is about 4700 m/s and the density is 7800 Kg/m^3 (thickness mode) and therefore the acoustic impedance (velocity x density) is $36.7x10^6$ Rayl. Human tissue on the other hand can be approximated acoustically as water which has a velocity of 1482 m/s and a density of 1000 kg/m^3 and therefore the acoustic impedance is about $1.5x10^6$ Rayls. This leads to a high acoustic mismatch (factor of 25) and therefore it does not allow for the efficient transmission of acoustic power to/from the tissue (water). Techniques over the years have been used to create matching layers of intermediate material between the transducer and the test media. However, even when using ¼ wave matching layers the coupling of the acoustic pressure from the transducer to the tissue is quite small compared to the available pressure (12 %). In addition many matching layer materials with acoustic impedances matching at the level of 6-8 Rayls are fabricated with two phase mixing of components which increases the chance of inhomogeneities and decreases the mechanical Q and thereby reduces the efficiency of transduction.
This technique uses an ultrasonic horn that allows for matching acoustic loads for large work pieces at relatively low frequencies. For this purpose, various ultrasonic horn configurations (stepped, linear, exponential, parabolic, Fourier etc.) have been develop to obtain the required matching. Piezoelectrics materials such as PZT produce a small displacement and a large stress. We have taken this capability to match the impedance and expanded it to the ultrasonic range. This is accomplished by connecting solid micromachined horn arrays that are sandwiched between a base-plate and a face-plate that are connected on one end to the transducing material (piezoelectric, electrostrictive, magnetostrictive etc.) and the medium to which the acoustic energy is to be transfer to or received from it. These solid horn arrays act as an efficient matching layer by amplifying the strain produced by the transducing material and generate greater displacement on the medium side and thereby transmitting more power to the load. The technology is applicable to a variety of modern manufacturing techniques such as silicon micromachining. Silicon micromachining for other purposes has been demonstrated to produce pillars of the order of 30 microns in diameter and 100-200 microns long. (eg. See reference [7] SEM photographs downloaded (02/06/2008) at http://www.ee.washington.edu/research/mems/intracellular/). It should be noted that thse matching layers can be optimized for lower frequency devices as found in energy harvesting and active

damping. In addition the approach can be used to design transducers with better coupling to air with larger power densities which may allow other mechanisms and devices currently not feasible.

3. THEORY

A schematic drawing of the Solid Micro Horn Array (SMIHA) Matching Layer is shown in Figure 1. This configuration is an array of square pillars connected by a base-plate (attached to the transducer) and a faceplate (attached to the load). The piezoelectric layer and the horn array both resonate at quarter wavelength. To ease the analytical modeling of the design one can assume initially a simple 1D model for the SMIHA structure and this structure can be generalized to the design shown in Figure 2 and Figure 3.

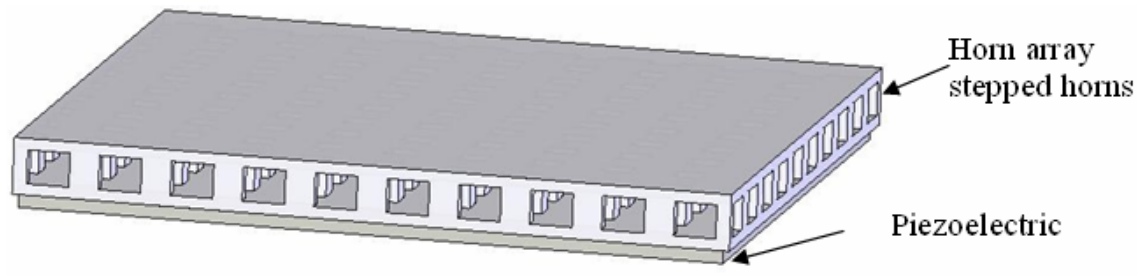

FIGURE 1: A graphic illustration of an array of square shaped rods (stepped horn array) connected to a base-plate (bottom) and a faceplate (top). The base-plate is attached to the piezoelectric layer. Sidewalls are not shown.

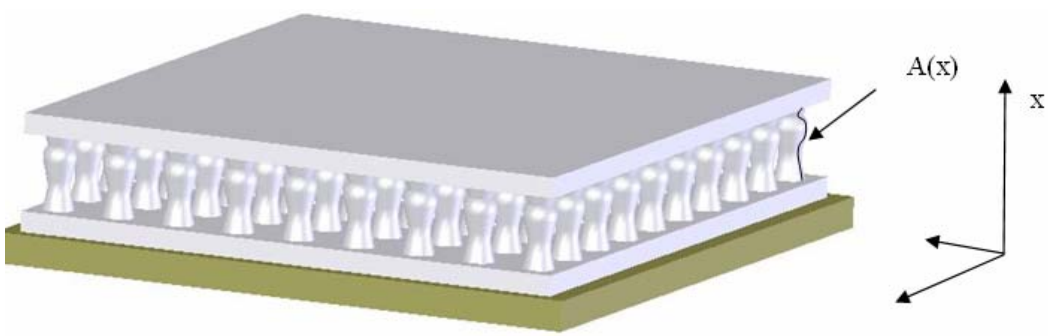

FIGURE 2: A solid-model view of generalized solid horn array matching layer. The horns have a cross sectional area A(x) that is a function of the thickness dimension x. Sidewalls are not shown.

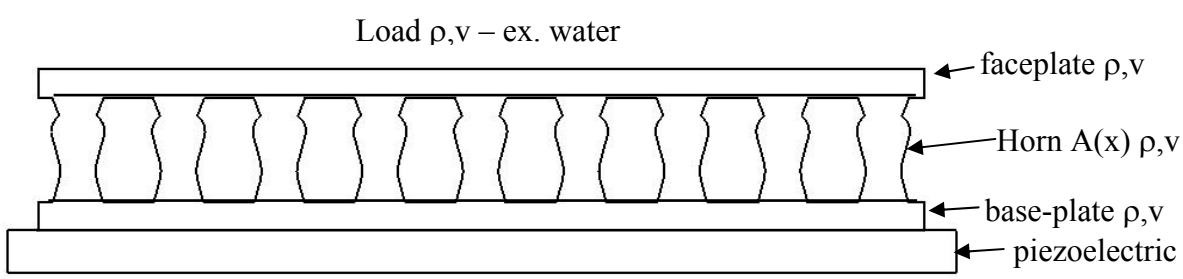

FIGURE 3: A cross section of a solid-model view of generalized solid horn array matching layer.

In Figure 3, the horns have a cross sectional area A(x) that is a function of the thickness with dimension x. Other design variables include the horn spacing (see Figure 2 and 4). One could conceive of horns that are distributed in another two dimensional arrangement without equal spacing or that are axis-symmetric (ex. concentric rings) which may be used to control the displacement at the face-plate load interface. A limiting factor in these SMIHA arrays is the horn element diameter or width and the horn spacing. The diameter or width must be chosen to produce lateral resonance (radial or width mode) that is above or below the thickness mode resonance frequency.

The horn array shown in Figure 1 was modeled using titanium, silicon, and inactive PZT as the matching layer material with a one dimensional Mason Equivalent Circuit model [8], [9]. The general structure that the model corresponds to is shown below in Figure 4. The electromechanical equivalent circuit is shown in Figure 5. It is a 4 layer model with the piezoelectric layer, backing plate and face plate all have the same area A. The horn layer area is *x*A a fraction of the total area A. The parameters of the circuit model are shown in Table 1. The electromechanical equivalent circuit for a mechanical layer is shown in Figure 6. In the modeling we have assume that the density and velocity in the layers is the same. The acoustic power per volt for the various solutions is shown in Figure 7 compared to the bare and perfectly matches matching layer solution. The parameters used for the models are shown in Table 2.

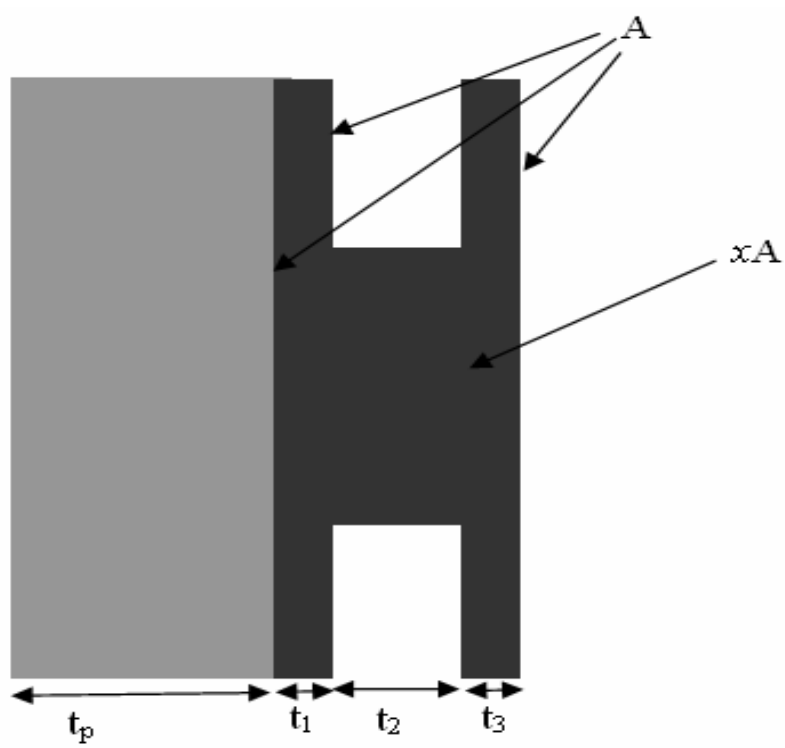

FIGURE 4: A cross section of a generalized solid horn array matching layer for use in one dimensional modeling.

The results show that the bandwidth of the Titanium and Silicon horn arrays is comparable or better than the perfectly match layer or the bare transducer. The amplitude except for a narrow range on the bare transducer is over a factor of two larger at other frequencies. The efficiency of transmission is shown in Figure 8. The results indicate that the efficiency of the matching layer can

be increased dramatically by producing the layers via micromachining and low loss materials such as Silicon and Titanium.

Table 1: Mason's equivalent circuit parameters as a function of the material coefficients and geometry

Mason's Model	
$\mathbf{C}_0 = \frac{\boldsymbol{\varepsilon}_{33}^S A}{t}$	$\mathbf{N} = \mathbf{C}_0 \boldsymbol{h}_{33}$
$\boldsymbol{Z}_0 = \rho\, A \mathbf{v}^D = A\sqrt{\rho\, \mathbf{c}_{33}^D}$	$\boldsymbol{\Gamma} = \frac{\omega}{\mathbf{v}^D} = \omega\sqrt{\frac{\rho}{\boldsymbol{c}_{33}^D}}$
$Z_T = i\mathbf{Z}_0 \tan(\boldsymbol{\Gamma} t/2)$	$Z_S = -i\mathbf{Z}_0 \csc(\boldsymbol{\Gamma} t)$

Table 2: piezoelectric and matching layer properties used in the modeling.

Piezoelectric Properties[10]		
Piezoelectric charge coefficient e_{33}	(C/m^2)	22.2-1.08i
Elastic stiffness constant D c^D_{33}	(N/m^2)	$1.74\text{x}10^{11} + 2.96\text{x}10^{9}$i
Clamped permittivity ε^s_{33}	(F/m)	$1.02\text{x}10^{-8} - 6.83\text{x}10^{-10}$
Thickness	(m)	10^{-4}
Area	(m^2)	$1.96\text{x}10^{-5}$
Horn Properties		
Titanium		
Velocity	(m/s)	5150(1+.0006i)
t1, t2, t3	(μm)	20, 40, 5
Area ratio x		0.25
Silicon		
Velocity	(m/s)	8430(1+.001i)
t1, t2, t3	(μm)	20,40,20
Area ratio x		0.25
Inactive PZT		
Velocity	(m/s)	4727(1+.0049i)
t1, t2, t3	(μm)	20,40,5
Area ratio x		0.2

Piezoelectric	Layer 1	Layer 2	Layer 3	Water
$\boldsymbol{\varepsilon}_{33}^{S}$ clamped complex permittivity	ρ_1	ρ_2	ρ_3	ρ_w
$\mathbf{c}_{33}^{D}$ open circuit complex elastic stiffness	v_1	v_2	v_3	v_w
$\boldsymbol{k}_t$ complex electromechanical coupling	A	xA	A	A
density ρ, area A, thickness t	t_1	t_2	t_3	$t_3 = \infty$

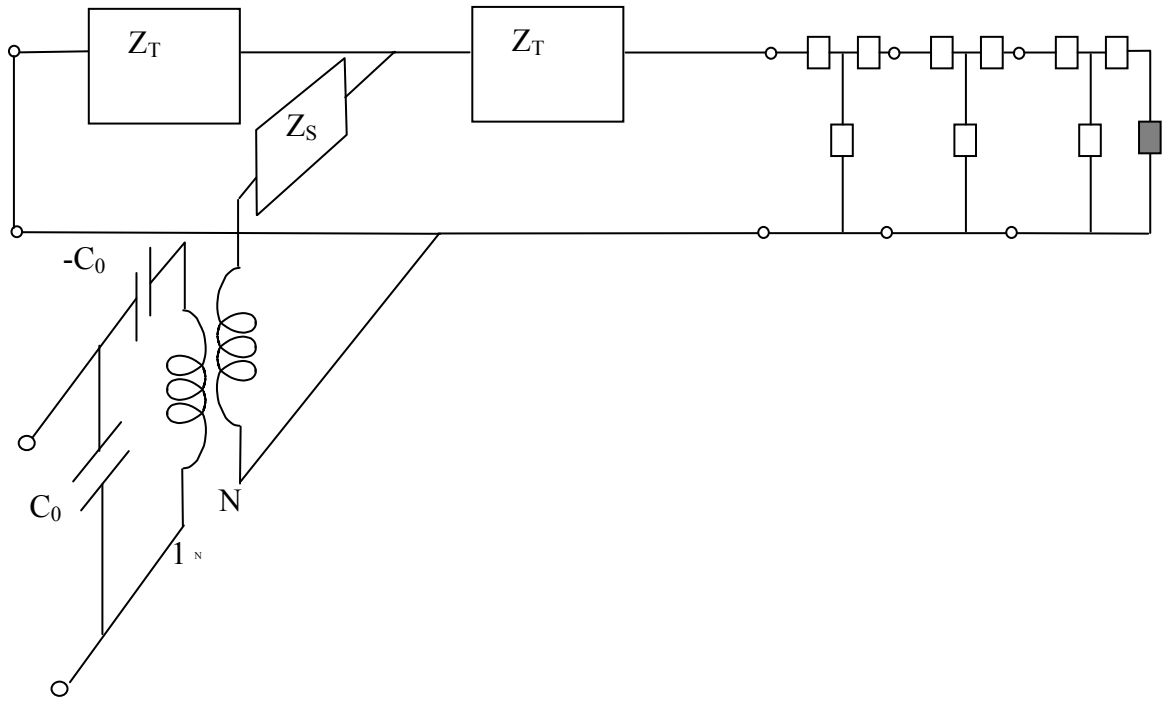

FIGURE 5: Mason's equivalent circuit for a piezoelectric and three mechanical layers

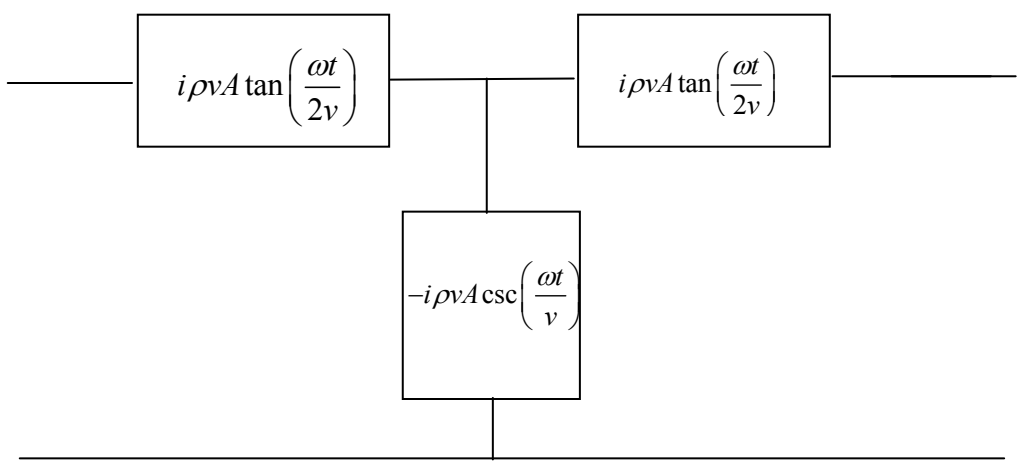

FIGURE 6: Electromechanical equivalent circuit elements for a mechanical layer

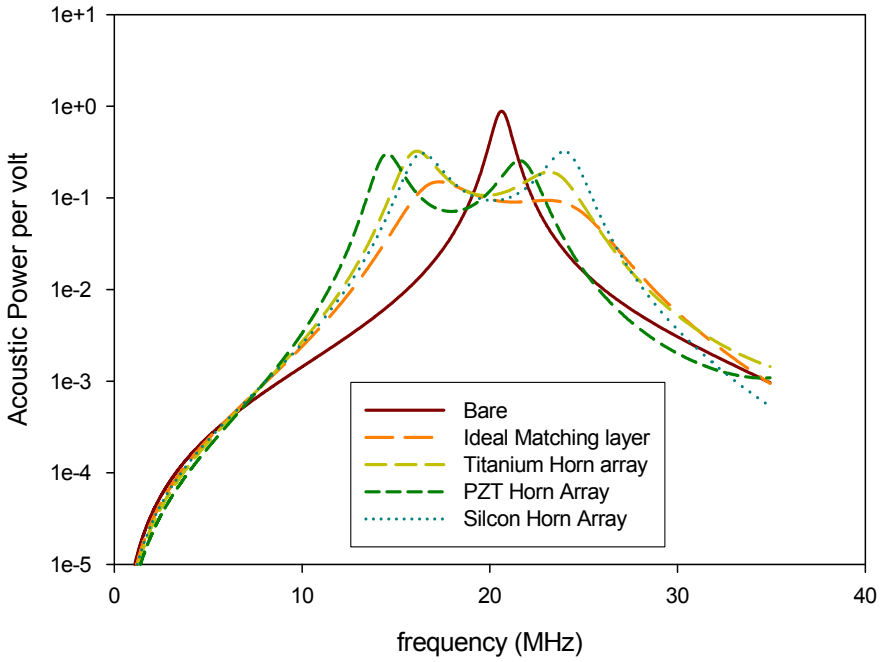

FIGURE 7: The acoustic power/volt as a function of frequency. Three horn types are compared to a bare and perfectly matched quarter wave matching layer.

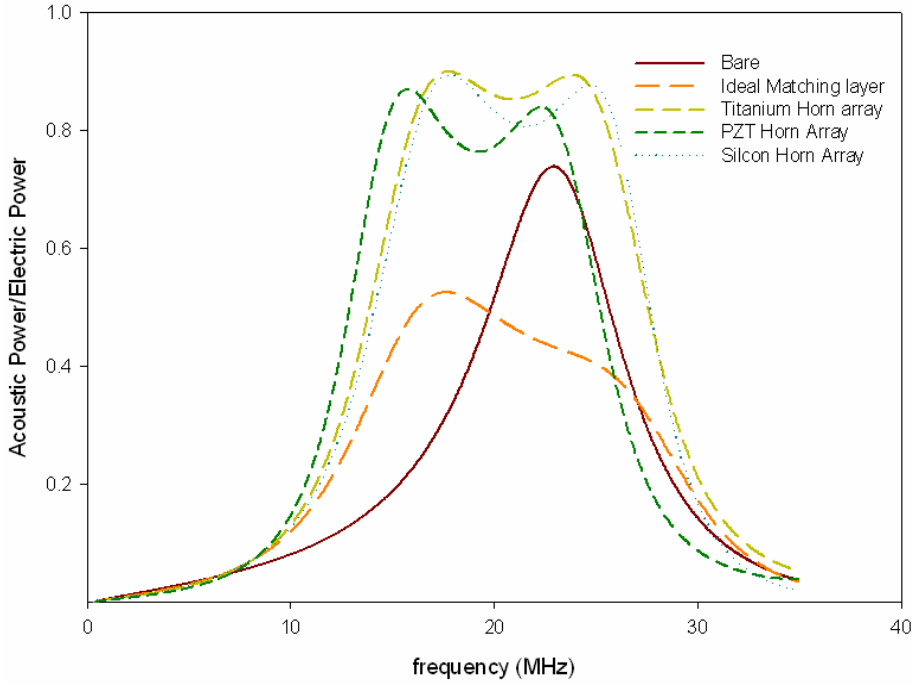

FIGURE 8: The efficiency of transduction for the horn array matching layers compared to bare transducer and the perfectly matched transducer.

4. FEM MODELING

In order to verify the 1D model we modeled the transducer elements in 2D ANSY. The finite element model is shown in Figure 9. In order to simulate a water load on the structure we used a critically damped layer with acoustic impedance $Z = \rho_w v_w A$. The material properties (velocity and the density) for silicon for the layer materials and the geometry as listed in Table 2. In order to compare the 1D model with the FEM model we set all the losses in the constants to zero in the 1D model and recalculated the pressure on the face of the element in contact with the water as a function of the frequency and compared this to the pressure generated by the FEM model. The results are shown in Figure 10.

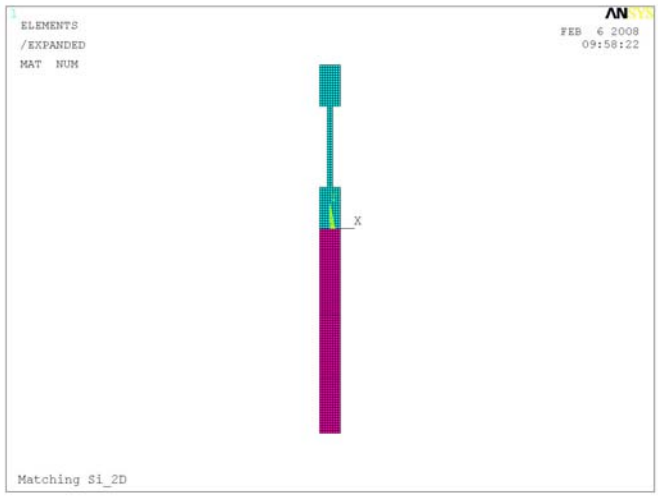

FIGURE 9. The finite element model for one element of micro-horn matching layer.

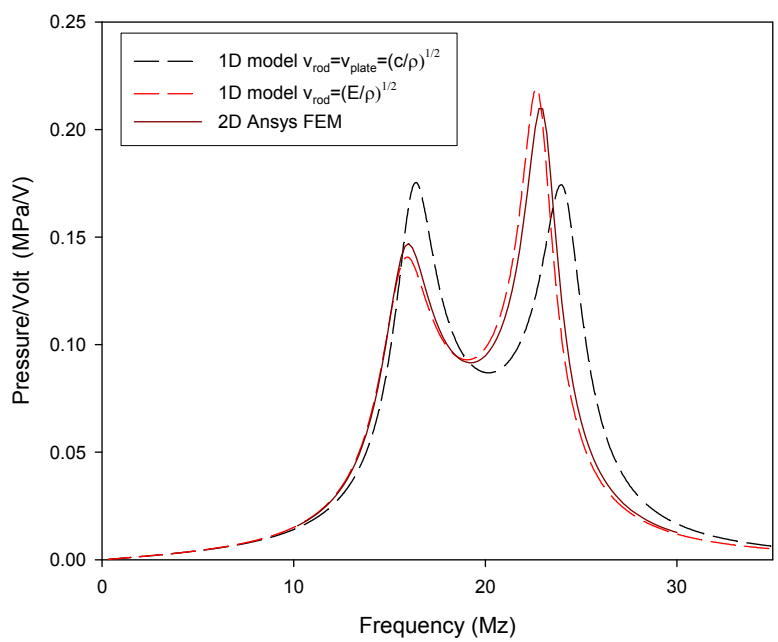

FIGURE 10. The pressure per volt for the lossless 2D ANYS model of a Silicon microhorn array matching layer and the 1D Mason's model with the acoustic velocity in all sections of the layer constant and equal to the plate velocity and with the velocity in the thin element of the array equal to the rod velocity $(E/\rho)^{1/2}$.

The 1D lossless Mason's model with constant velocity in the plate and the 2D ANSYS model were found to produce some measurable differences in the Pressure frequency spectra. The peaks for the 1D model were higher in frequency and symmetric compared to the peaks from the ANSYS model. This was expected since the surface of the thin rod section of the matching layer is unconstrained and the rod is less stiff than the plates. To improve the accuracy of the 1D model we used the rod velocity $(E/\rho)^{1/2}$ rather than the plate velocity $(c/\rho)^{1/2}$ in the middle section of the matching layer. With this modification the curves from the ANSYS and the 1D Mason's model were found to almost match.

5. SUMMARY

We have presented a new approach to matching layers that utilizes the primary property of horns to acoustic match in the low frequency regime and by miniaturizing and arraying them we demonstrate theoretically that ideal matching layers that have excellent bandwidth and efficiencies can be designed. Since these are monolithic structures they can be manufactured from one material and the material can be chosen to minimize acoustic loss and heat generation in the matching layer. The approach is also amenable to MEMS fabrication, Silicon integration and micromachining, tape casting, laser micro-machining and multilayer co-fired fabrication techniques

.ACKNOWLEDGMENT

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