IMPROVED ACOUSTIC COUPLING OF AIR-COUPLED MICROMACHINED ULTRASONIC TRANSDUCERS
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ABSTRACT
Phased array imaging with micromachined ultrasound transducer (MUT) arrays is widely used in applications such as ranging, medical imaging, and gesture recognition. In a phased array, the maximum spacing between elements must be less than half of the wavelength to avoid large sidelobes. This places a limit on the maximum transducer size which is not attractive since the acoustic coupling drops rapidly for MUT diameters less than a wavelength.

Here, we present a new approach to increase the acoustic coupling of small radius MUTs using an impedance matching resonant tube etched beneath the MUT. Impedance, laser Doppler vibrometer (LDV), and acoustic burst measurements confirm a 350% increase in SPL and 8x higher bandwidth compared to transducers without the impedance matching tube, enabling compact arrays with high fill-factor and efficiency.

INTRODUCTION
Air-coupled micromachined ultrasound transducers (MUTs) achieve maximum output sound pressure level (SPL) and bandwidth when the radius, $a$, approaches the acoustic wavelength, $\lambda$. This requirement imposes a significant limitation on the minimum achievable transducer size for both piezoelectric micromachined transducers (PMUTs) and capacitive MUTs (CMUTs), particularly for transducers operating in array configurations. For transducers employing a compliant plate structure and operating less than 200 kHz this typically results in transducers with radius greater than 0.5 mm [1-5]. In this paper, we explore the use of a resonant tube, etched into the backside of a wafer, to enhance the acoustic coupling and bandwidth of small scale transducers ($a \sim \lambda/8$) enabling a significant size reduction and enhanced array fill factors, without loss in transducer output SPL or bandwidth.

THEORY AND MODELING
The PMUTs presented here are designed for air coupled operation in a 2D array configuration at a nominal frequency of 200 kHz [6]. The PMUT, shown in Fig. 1, is a unimorph design based on a SiO₂/AlN/Mo/AlN film stack. The thickness of the AlN layers is 1 µm, the Mo and Al electrodes are 150 nm, and the SiO₂ is 100 nm. Detailed description of the design and fabrication of these devices can be found in our prior work [7, 8].

To illustrate the coupling performance we model the transducer, without the resonator tube, as a simple circular piston in an infinite baffle, the specific acoustic impedance (Rayl) of which is given by [9]:

$$Z_p(k_a) = Z_0 \left( 1 - \frac{2J_1(2ka)}{2ka} + \frac{2K_1(2ka)}{2ka} \right)$$

Where $Z_0 = 413$ Rayl is the characteristic impedance of air, $a$ is the radius of the piston, $k = 2\pi/\lambda$ is the wave number, $J_1$ is the Bessel function of order 1, and $K_1$ is the Struve function of order 1. The normalized real and imaginary parts of $Z_p$ are plotted in Fig. 2. The real part of the acoustic impedance, $Re(Z_p)$, determines the power radiated to the air. Small PMUTs ($ka < 2$) experience reduced acoustic impedance relative to larger transducers. Consequently, the stored mechanical energy is much larger than the radiated energy, resulting in narrow bandwidth and poor coupling. The PMUTs presented in this work have $ka \sim 0.7$ which results in $Re(Z_p)$ that is only 22% of $Z_0$.

Here, to enhance acoustic coupling and bandwidth, DRIE is used to create a tube resonator extending from the back of the wafer to the bottom of the PMUT membrane. Appropriate design of the tube dimensions results in an acoustic resonance that occurs at the same frequency as the mechanical resonance of the PMUT, thereby increasing the real acoustic impedance seen by the PMUT. The result is that the transducer’s bandwidth is dramatically increased and the SPL emitted from the tube is several times greater than the SPL emitted from the front of the PMUT membrane.

Equivalent Circuit Model
An equivalent circuit model of the transducer and resonator tube acoustics is shown in Fig. 3. Building on our previous work with the electrical and mechanical portions of the model [10] the acoustic tube resonator is added as a transmission line element. The modal mass and stiffness used in the analytic model are extracted from impedance
and laser Doppler vibrometer (LDV) measurements [10] for transducers with resonant frequencies of ~230 kHz and are $m_a=0.197$ ng, and $k_m=308$ N/m respectively. In the acoustic domain we model the plate as a baffled piston. We assume a clamped plate model with a normalized plate deflection shape function of [11]:

$$\varphi(x) = (1 - x^2)^2$$

where $x$ is the radial coordinate. Since we are modeling the acoustic source as a piston, we define an effective radius for this piston, $a_{eff}$, such that the piston, moving with the peak velocity of the plate, has the same volume velocity as that of the flexing plate. The acoustic impedance (Rayls/m²) of the front side of the plate is also a baffled piston with effective radius, $a_{eff}$:

$$Z_{front} = Z_{baffle}(ka_{eff}) = \frac{Z_p(k a_{eff})}{\pi a_{eff}^2}$$

Although this impedance is a function of wavenumber $k$ (or, equivalently, frequency $f$), in what follows we use compact notation and omit the explicit dependence on $k$. At the throat (open end) of the tube, moving air also encounters an acoustic impedance which is that of a baffled piston but the entire radius contributes:

$$Z_{th} = Z_{baffle}(ka) = \frac{Z_p(k a)}{\pi a^2}$$

The impedance of the acoustic transmission line is the acoustic impedance of the medium divided by the cross sectional area of the tube, $Z_{tube} = \frac{Z_0}{\pi a^2}$. To calculate the impedance seen by the backside of the plate we calculate the reflection and transmission coefficients for the throat of the tube as [9]:

$$R_{th} = \frac{Z_{th} - Z_{tube}}{Z_{th} + Z_{tube}}$$

$$T_{th} = \frac{2Z_{th}}{Z_{th} + Z_{tube}}$$

and the impedance of the backside of the plate:

$$Z_{back} = \frac{e^{ikd} + R_{th} \cdot e^{-ikd}}{e^{ikd} - R_{th} \cdot e^{-ikd}}$$

The total acoustic impedance seen by the plate is then:

$$Z_{total} = Z_{front} + Z_{back}$$

and the total air damping is:

$$b_{air} = (\pi \cdot a_{eff}^2)^2 \cdot \text{Re}(Z_{total})$$

The acoustic damping is the dominant damping element and therefore the bandwidth is:

$$BW = \frac{b_{air}}{2\pi m_a}$$

As a result of the tube’s acoustic resonance, the pressure at the tube’s throat is greater than that on the front face of the PMUT, a phenomenon we describe as resonator gain. The impedance seen looking into the tube from $Z_{th}$, defined as $Z_{fm}$, is the sum of $Z_{front}$ and the mechanical equivalent circuit impedances transformed into the acoustic domain using an ideal transformer:

$$Z_{fm} = Z_{front} + \frac{1}{(\pi a_{eff}^2)^2} \cdot (i2\pi f m a^2 + k_m i2\pi f_n$$

Similarly, the reflection and transmission coefficients at the plate end of the tube are given by:

$$R_p = \frac{Z_{fm} - Z_{tube}}{Z_{fm} + Z_{tube}}$$

$$T_p = \frac{2Z_{fm}}{Z_{fm} + Z_{tube}}$$

To calculate the tube gain we consider a Thévenin equivalent pressure source and impedance seen by the throat (load) impedance at the end of the tube:

$$P_{eq} = \frac{P_{in}}{\cos(kl)} \cdot \left( -\frac{i Z_{tube} \cot(kl)}{Z_{fm} - i Z_{tube} \cot(kl)} \right)$$

$$Z_{eq} = Z_{tube} e^{ikl} + R_p \cdot e^{-ikl}$$

Where $P_{in} = \frac{n}{\pi a_{eff}} \cdot V_{in}$ is the input pressure and $l$ is the
length of the tube. The Thévenin equivalent circuit is shown in Fig. 4. Using these parameters, we calculate the gain from the pressure on the tube-side transducer face to the pressure at the throat:

\[
G_{tx} = \left| \frac{P_{ex}}{P_{fm}} \right| = \left| \frac{-iL_{tube} \cot(\theta_L)}{Z_{fm} - iL_{tube} \cot(\theta_L) \cos(\theta_L)} \right|
\]

Finally, the resonator gain, defined as the ratio of the pressure magnitude at the throat of the tube to the pressure magnitude at the front side of the transducer, is calculated as:

\[
G_{resonator} = \left| \frac{P_{th}}{P_{front}} \right| = \left| \frac{G_{tx} (Z_{back} + Z_{fm})}{Z_{th} + Z_{eq}} \right|
\]

**Finite Element Model**

The PMUT’s dynamic response is modeled using a two dimensional axisymmetric piezo-acoustic finite element method (FEM) model implemented in COMSOL. The piezoelectric portion of the model is a fixed laminated circular plate that consists of two AlN layers, each of 1 μm thick. The passive (bottom) layer is defined as a linear elastic material while the active (top) layer is defined as a piezoelectric material. An alternating voltage is applied across 70% of the radius of the active piezoelectric layer, corresponding to the radius of the PMUT’s top electrode.

The simulation geometry and output pressure field are shown in Fig. 5. The tube boundary condition is defined as a perfectly reflecting wall. The air surrounding the transducer is modeled as two 5 cm radius half spheres (not fully shown in Fig. 5) bounded by a perfectly matched layer. The two spheres, as well as the interior of the tube are defined as air with a theoretical attenuation constant calculated at 200 kHz [9]. The SPL is probed at two points, one on each sphere’s matched layer, located on the axis of symmetry.

**Modeling results**

The predicted resonator gain frequency response for different tube lengths is shown in Fig. 6 for both the FEM and equivalent circuit models. The maximum resonator gain occurs at a frequency that varies with tube length. The analytic and FEM models are in good agreement and show that output pressure gains >8x are possible depending upon the frequency of operation and tube design. For our nominal design, we predict a resonator gain of 4 on both transmit and receive at a frequency of ~217kHz. This is equivalent to increasing the \(\text{Re}(Z_{Baffle})\) to 88% of the high frequency value, a significant improvement.

**EXPERIMENT**

Acoustic testing was performed using a burst measurement technique. The transducer was excited at its resonant frequency with 50 cycles of a 220 kHz sine wave and the pulse was received by a microphone placed 5 cm away. The time domain signal was filtered, amplified, and captured with an oscilloscope. The transmit pulse and received signals from the membrane and tube side of the tube are shown in Fig. 7. The measured resonator-side output SPL is 3.5x higher than the membrane-side SPL.
transducer are shown in Fig 7. Comparing the received bursts we can see resonator gain of 3.5 which matches closely with the theoretical and FEM predicted gain of 4. In addition, the resonant tube increases the transducer bandwidth due to the increased acoustic coupling. In this way the tube can be thought of as an acoustic matching layer. To demonstrate the effect on the bandwidth we measured the frequency response, in air, of ~250 PMUTs with identical dimensions and varying acoustic wavelengths using a LDV. The acoustic wavelength variation in the transducers is due to residual stress variation in the thin film layers. Fig. 8 shows the measured bandwidth and the bandwidth predicted by the analytic model with and without the acoustic resonator. In the model, a constant mass \( m_a \) is assumed and the stiffness \( k_m \) is varied to yield varying resonant frequency. The analytic model results illustrate an increase in bandwidth of 8x over a transducer without the tube.

**CONCLUSION**

In this paper we have presented a method to improve the acoustic coupling and bandwidth of small radius micromachined ultrasound transducers. An equivalent circuit analytic model is presented and the results compared with a 2D-axisymmetric piezo-acoustic finite element simulation. Fully clamped circular PMUTs with a radius to wavelength ratio of 11% were fabricated and characterized in the electrical, mechanical, and acoustic domains. An acoustic gain of 350% is demonstrated using transducers with a resonant tube 250 \( \mu \)m in length. This is equivalent to increasing the \( Re(Z_{p}) \) to 88% of the large diameter value, a significant improvement. In addition, measurements reveal peak bandwidths of \( >20 \) kHz (FWHM) for transducers with a resonator tube. Analytic modeling shows this is an 8x increase in bandwidth over transducers without the acoustic resonator tube. The increase in output pressure and bandwidth allows for the use of high fill factor arrays rather than a single large transducer, which opens up new applications for air coupled MUTs as well as increasing the performance of existing systems.

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