DOI 10.5162/Ultrasonic2025/C3-a2

Investigating the Acoustic Focusing Performance of PDMS Lens for Ultrasound Transducers

Venkata Shanmukha Srivatsav Pakki[1,2], *Meghana Vishwanatha*[1], *Nooshin Saeidi*[1,2], *Markus Guttman*[3,4], *Celine Deutschbein*[3,4], *Karman Selvam*[1], *Maik Wiemer*[1], *and Harald Kuhn*[1,2]
[1] *Fraunhofer ENAS, Chemnitz, Germany*
[2] *Technische Universität Chemnitz, Chemnitz, Germany*
[3] *Institute of Microstructure Technology, Eggenstein-Leopoldshafen, Germany*
[4] *Karlsruhe Institute of Technology, Eggenstein-Leopoldshafen, Germany*
venkata.shanmukha.srivatsav.pakki@enas.fraunhofer.de

Abstract: This study investigates acoustic focusing using a PDMS convex lens. The results revealed that the lens caused a shift in the focal region towards the transducer, as observed in experiments and simulations. The lens reduced near-field interference, increased output pressure, and improved beam convergence as indicated by a narrower beam profile. These findings highlight the potential of PDMS lenses for optimizing the performance of ultrasound transducers, including micromachined ultrasound transducers (MUT's), for various applications.

Keywords: Ultrasound transducers, acoustic lens, polydimethylsiloxane (PDMS), acoustic focusing, acoustic beamforming

Introduction

Acoustic focusing allows precise convergence of the ultrasound beam to a specific point enabling effective beam control suitable for applications such as medical imaging [1], particle manipulation and therapy [2]. Three principal strategies are used to create a focal region: geometric focusing of single element transducers, electronic phasing of array of elements, and acoustic lensing. Acoustic lensing will be the primary focus in this paper.

• ***Acoustic Lensing:*** The manipulation of sound waves can be achieved using materials or structures engineered to refract acoustic energy. An acoustic lens, often made of a polymer, alters the propagation of sound wave to create a converging or diverging wavefront.

When an acoustic wave propagates across media with differing acoustic properties (characterized by acoustic impedance Z and speed of sound v), refraction occurs according to Snell's law :

Eq. (1).

$$\frac{\sin(\theta_l)}{V_l} = \frac{\sin(\theta_m)}{V_m} \tag{1}$$

where θ_l and θ_m represent the angles of incidence and refraction, V_l and V_m represent the speed of sound in lens and medium respectively [3].

By carefully selecting lens materials and designing lens geometries, acoustic lenses can effectively control wave propagation. The effectiveness of acoustic lensing is significantly dependent on minimizing reflection losses at interfaces while maximizing transmission efficiency.

The implementations of acoustic lenses often involved solid shaped [4] and liquid-filled structures [5] designed to exploit refractive differences in lens and medium. The primary application of acoustic lensing are as follows:

a. Converging (focusing) lens – A convex lens with $V_\mathrm{l}<V_\mathrm{m}$ or a concave profile with $V_\mathrm{l}>V_\mathrm{m}$ causes waves to bend toward the axis, thus shortening the focal distance, increasing the signal to noise ratio (SNR) and on-axis pressure. Converging lenses are mostly used for medical ultrasound imaging [4] applications.

b. Diverging lens – When $V_\mathrm{l}>V_\mathrm{m}$, a convex profile or a concave profile with $V_\mathrm{l}<V_\mathrm{m}$ can also achieve divergence. Such designs are often employed to expand the field-of-view in large-area, in flat row–column-addressed (RCA) applications [6].

Polymers are often chosen for lens fabrication due to their suitable range of acoustic impedances such as Poly dimethyl siloxane (PDMS) [4] , Poly Urethane (PU) [7], and Room-temperature-vulcanizing silicone (RTV) [7]. The radius of curvature (R), diameter of transducer (D), thickness of lens (TL) and thickness of collar (TC), and geometrical focal length (F_geo) as illustrated in Fig. 1, are critical geometric parameters that influence acoustic focusing. Acoustic lenses are fabricated in various shapes, such as convex [4] and concave [6] geometries. Key goals of lens adaptation, include improving focusing capabilities, adapting the field of view, and achieving optimal resolution at varying depths.

This study investigates the acoustic focusing of ultrasound waves using a PDMS based convex lens.

DOI 10.5162/Ultrasonic2025/C3-a2

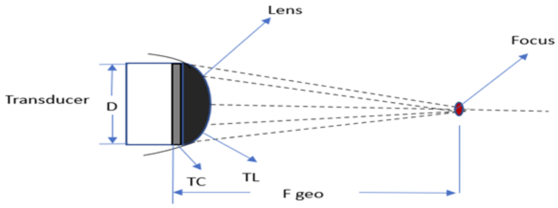

Fig. 1: Schematic of acoustic focusing using convex lens.

Tab. 1: Simulation parameters for acoustic focusing.

Design parameters	Values
Resonant frequency	2 MHz
Transducer diameter	10 mm
PDMS (speed of sound)	$970\,\mathrm{m\,s^{-1}}$
PDMS (density)	$1105\,\mathrm{kg\,m^{-3}}$

In this study we simulated, designed, fabricated and tested a convex PDMS lens on a piezo disc ultrasound transducers, operating in an oil medium at ambient temperature.

Method

This research work began with the design and simulation of the lens using k-Wave tool box in MATLAB software to assess its influence on acoustic characteristics. The results from the simulations were used as inputs to model and fabricate the PDMS convex lens. The lens was then characterized experimentally. The detailed methodology is described below.

1. **Design and Simulations:** The system, including the lens, transducer, and coupling medium, was modeled using the k-Wave toolbox in MATLAB to simulate acoustic wave propagation and focusing behavior. Initially, the beam profile of an unfocused ultrasound disc transducer, whose specifications are detailed in i.e. Tab. 1 was simulated in oil medium. The transducer was excited using a 3-cycle of sine wave burst. Simulations were conducted at the transducer's resonant frequency to evaluate their influence on beam profile, beam width, focusing and pressure distribution. To examine the role of lens, subsequent simulations were performed by introducing a convex PDMS lens positioned on top of the transducer. The simulations were performed with varying lens thicknesses(2, 2.5, 3 mm). The resulting variations in the aforementioned parameters were analyzed to gain insight, into the focusing behavior and beam-shaping effects influenced by the lens structure.

Fig. 2: Pictures of transducer without lens (a), 2.5mm convex lens (b), 3mm convex lens (c).

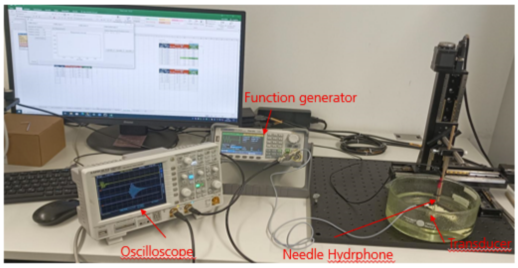

Fig. 3: Experimental setup.

2. **Lens fabrication:**

   The PDMS lens was custom-fabricated in convex shape. Both the transducer holder and the concave lens mold were 3D-printed to match the desired specifications based on simulation parameters. Sylgard 184 polymer was used as the lens material, the elastomer and curing agent were mixed in a 10:1 ratio by weight. The mixture was then degassed under vacuum to eliminate air bubbles, then cast over the disc transducer and into the lens mold. It was subsequently cured at room temperature for 48 hours. The fabricated lens is shown in Fig. 2.

3. **Experimental setup:**

   The fabricated lens was tested experimentally to evaluate the acoustic focusing effect as shown in Fig. 3. A needle hydrophone (Müller Hydrophone, sensitivity - 1.3 mV/bar) was positioned above the transducer using an XYZ translation stage to scan the acoustic field above the transducer. A function generator (Sigilent SDG 2042X Function generator) was used to produce a 3-cycle sine burst excitation signal, and an oscilloscope(Hameg Instruments HM0722, 2 channel, 70MHz digital oscilloscope) was employed to monitor both the input and output signals.

Results

The results are divided into simulations results and experimental results:

1. Simulation results: The simulation results for the unfocused ultrasound transducer revealed complex near field interferences, maximum output pressure of

DOI 10.5162/Ultrasonic2025/C3-a2

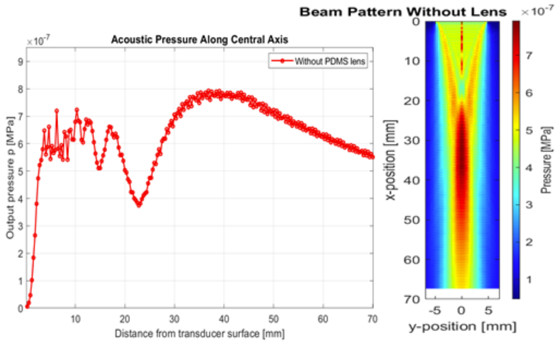

Fig. 4: Simulation results for without lens

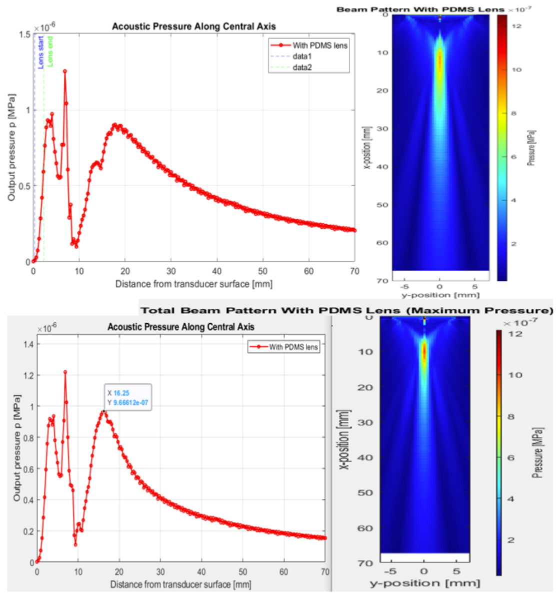

Fig. 5: Simulation results for lens thickness 2 mm(top), 2.5 mm(bottom)

0.8 Pa, focal point at ca. 38 mm and wide (unfocused) beam profile depicted in i.e. Fig. 4 .

The simulation from the 2.0 mm lens, resulted in output pressure of 0.9014 Pa, focal point shifted towards the transducer (to 17.81 mm), a focused (narrower) beam profile was observed as shown in i.e. Fig. 5. Simulation with 2.5 mm lens led to an increased output pressure of 0.9666 Pa, a 7.23% increase relative to the 2.0 mm lens, with the focal point shifting (to 16.25 mm) towards the transducer, and a more narrower beam profile was observed as shown in i.e. Fig. 5). Conversely, the 3.0 mm lens resulted in a decreased output pressure of 0.8775 Pa, a 9.22% reduction compared to the 2.0 mm lens, focal point experienced the largest shift towards the transducer at 13.75 mm, producing the most focused beam profile as shown in i.e. Fig. 6. Based on the simulation results the 2.5

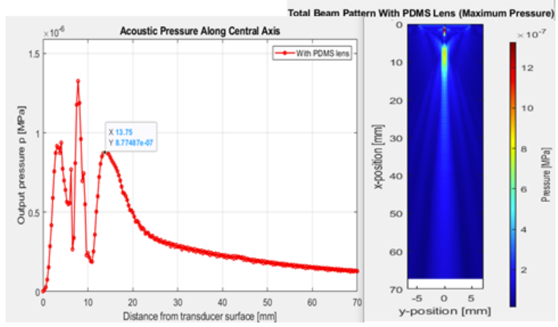

Fig. 6: Simulation results for with 3 mm lens

mm lens yielded the highest output pressure, while the 3.0 mm lens demonstrated superior focusing performance and hence these two thickness were selected for lens fabrication and experimental validation.

2. Experimental results: Initially a frequency sweep was performed to verify whether lens casting and integration affected the transducer's resonance; results showed no change for either the 2.5 mm or 3.0 mm lens. In the next experiment to identify the focal point or region using the XYZ stage, the needle hydrophone was moved with controlled step of 1 mm in Z axis. The focal point of the transducer (without lens) was observed at ca. 16.182 mm and with a peak to peak amplitude of 3.92 V. The results with addition of 2.5 mm lens showed a focal point at 13.746 mm i.e., a shift of 2.736 mm towards the transducer and with a peak to peak amplitude of 7.8 V. The experiment was repeated with a 3 mm lens which showed a focal point at 12.702 mm i.e., a shift of 3.48 mm towards the transducer and with a peak to peak amplitude of 7 V. There is also an decrease in the amplitude maximum at the focal point for 3 mm lens by 11.4% when compared to 2.5 mm thickness lens as shown in i.e. Fig. 7. As shown in Fig. 8, the convex lens significantly enhances the focusing capability of the initially unfocused transducer. Comparing output amplitude values which can be directly correlated to pressure, the trend is in agreement with the simulated results.

To analytically validate the focusing performance of the PDMS lenses, theoretical focal lengths were calculated using the Lens Maker's Equation and compared with values obtained from both simulations and experimental results. For the 3 mm PDMS lens, the theoretical focal length was approximately 11.215 mm, while the experimental value was 12.702 mm and the simulated value was 13.75 mm. Similarly, in the case of the 2.5 mm lens, the theoretical focal length was 12.370 mm, while the experimental and simulated focal lengths were found to be 13.746 mm and 16.25

DOI 10.5162/Ultrasonic2025/C3-a2

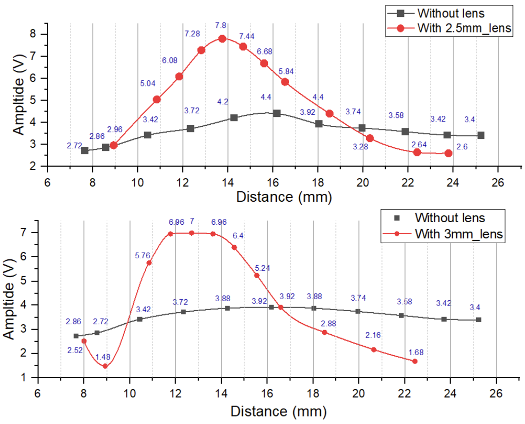

Fig. 7: Experiment results for lenses

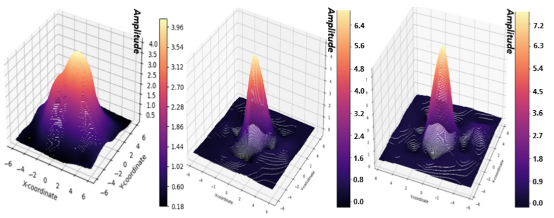

Fig. 8: Visualization of focused acoustic field from experimental measurements of without lens (left), 3mm lens (middle), 2.5mm lens (right)

mm, respectively. These results demonstrate good agreement among theoretical predictions, simulations, and experimental measurements in terms of shift of focal length, thereby validating the lens design and modeling approach. However, the pressure values obtained from simulations do not fully align with those calculated from the experimental amplitude measurements, likely due to factors such as system losses,and calibration differences. While the trends in focusing behavior are consistent, this discrepancy in pressure values highlights the need for careful calibration according to real time setup.

Conclusion

In this study, simulations and experiments were conducted using an ultrasound disc transducer in an oil medium, both without and with a convex shaped encapsulated PDMS lens. The results reveal important trade-offs in transducer design related to lens thickness. While thicker lenses (i.e., 3.0 mm) offer superior beam focusing and focal point closer to the transducer, they didn't yield the highest acoustic output pressure. Conversely, an intermediate thickness (i.e., 2.5 mm) yielded a better balance between acceptable focusing and enhanced pressure output. The discrepancies in output values result from idealized assumptions in the simulations, including the implementation of perfectly matched layers. The selection of an appropriate lens thickness would therefore depend on the specific application requirements or frequency characteristics of the transducer, prioritizing either maximum energy transfer at the focal point or the narrowest possible beam profile with maximum pressure.

Acknowledgment

The authors wish to thank the Center for Microsystems and nano technologies at Technische Universität Chemnitz and Karlsruhe Nano Micro Facility at Karlsruhe Institute of Technology for their valuable support.

References

[1] M. Audoin, A. Salari, B. G. Tomov, K. F. Pedersen, J. A. Jensen and E. V. Thomsen, 'Diverging polymer acoustic lens design for high-resolution row–column array ultrasound transducers,' *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, vol. 14, pp. 202–213, 2024, 10.1109/TUFFC.2023.3327567.

[2] S. Wang, X. Wang, F. You and H. Xiao, 'Review of ultrasonic particle manipulation techniques: Applications and research advances,' *Micromachines*, vol. 14, p. 1487, 2023, 10.3390/mi14081487.

[3] S. H. Øygard, M. Audoin, A. Austeng, E. V. Thomsen, M. B. Stuart and J. A. Jensen, 'Accurate prediction of transmission through a lensed row-column addressed array,' *The Journal of the Acoustical Society of America*, vol. 151, pp. 3207–3218, 2022, 10.1121/10.0010528.

[4] C. Chang et al., 'Acoustic lens for capacitive micromachined ultrasonic transducers,' *Journal of Micromechanics and Microengineering*, vol. 24, p. 085 007, 2014, 10.1088/0960-1317/24/8/085007.

[5] C. Song, L. Xi and H. Jiang, 'Acoustic lens with variable focal length for photoacoustic microscopy,' *Journal of Applied Physics*, vol. 114, p. 194 703, 2013, 10.1063/1.4832757.

[6] H. Bouzari et al., 'Curvilinear 3-d imaging using row–column-addressed 2-d arrays with a diverging lens: Phantom study,' *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, vol. 65, pp. 1182–1192, 2018, 10.1109/TUFFC.2018.2836384.

[7] S. Kim and J. Chang, 'Effect of acoustic properties of lens materials on performance of capacitive micromachined ultrasonic transducers,' *Journal of Medical and Biological Engineering*, vol. 36, pp. 536–544, 2016, 10.1007/s40846-016-0150-z.