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Enhanced Sound Energy Harvesting by Leveraging Gradient-Index Phononic Crystals

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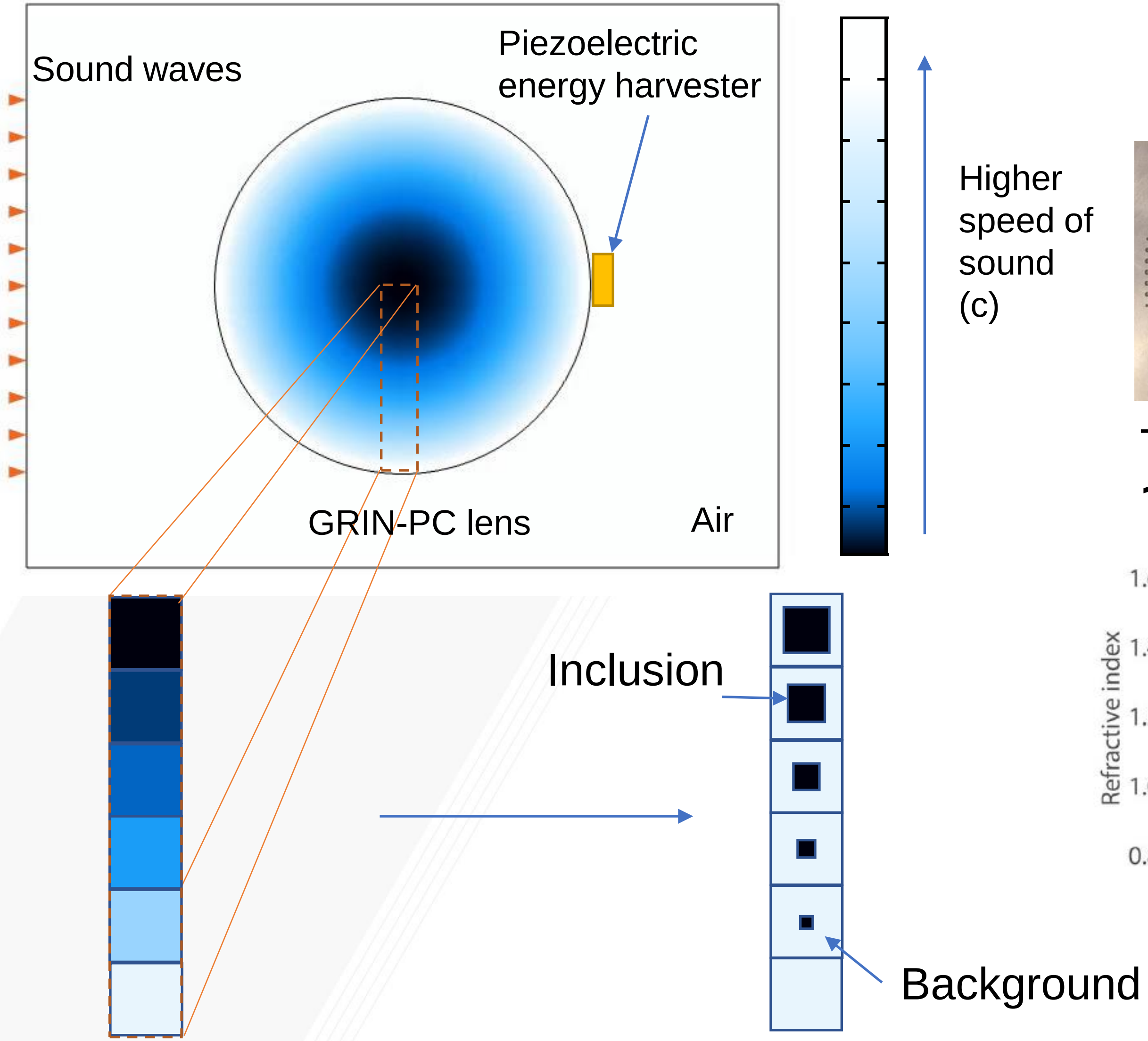
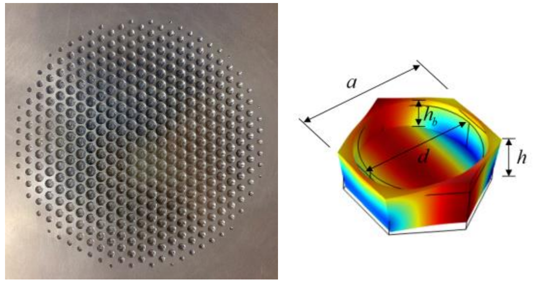
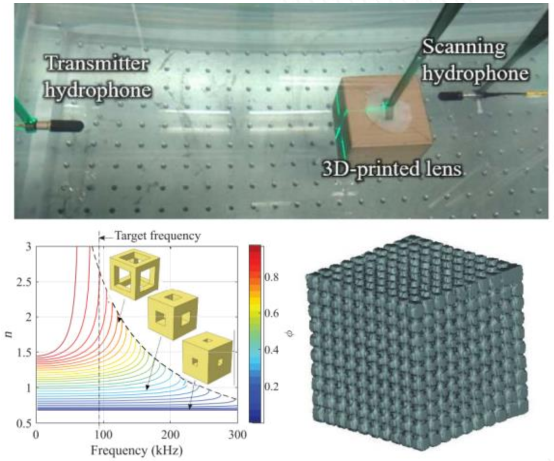
Background

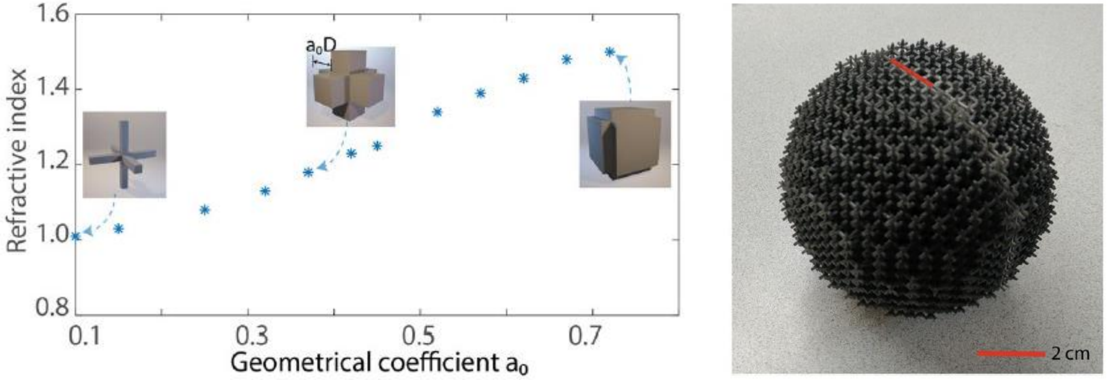




Tol *et al*. *Appl. Phys. Lett*. **111**, 013503 (2017).



Allam *et al*. *Phys. Rev. Applied* **13**, 064064 (2020).



Xie, Y. *et al*. *Sci. Rep*. **8**, 16188 (2018).

Motivation and Objective

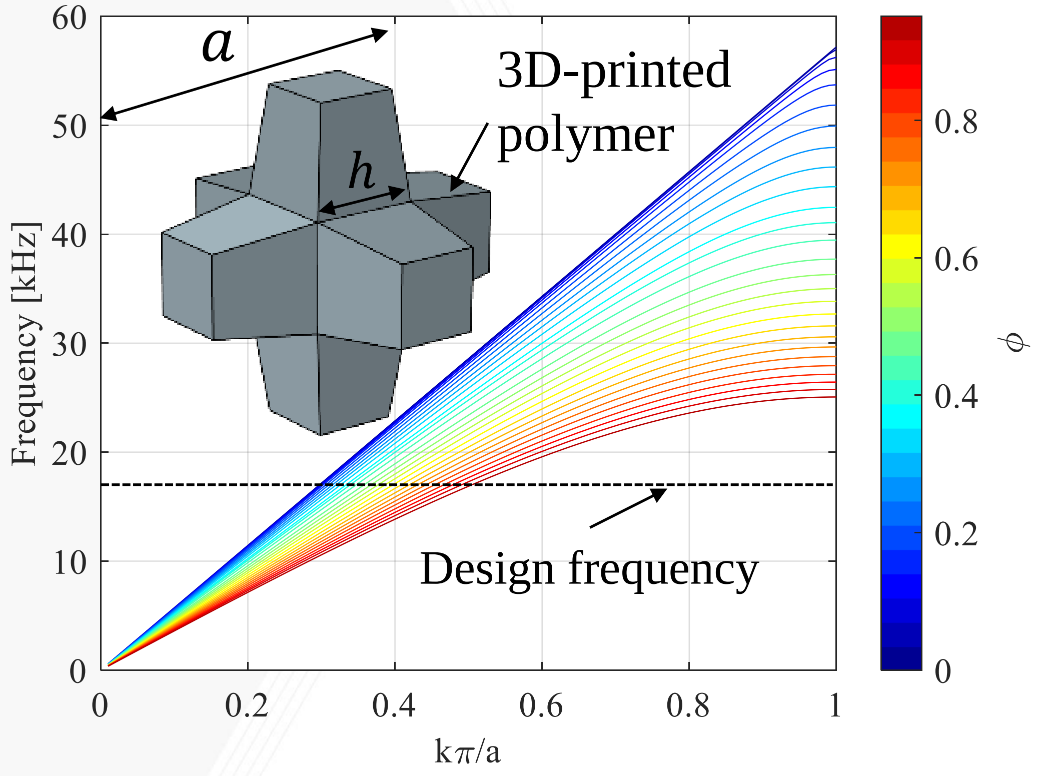
- Although sound energy is widely available, it has relatively low power density.

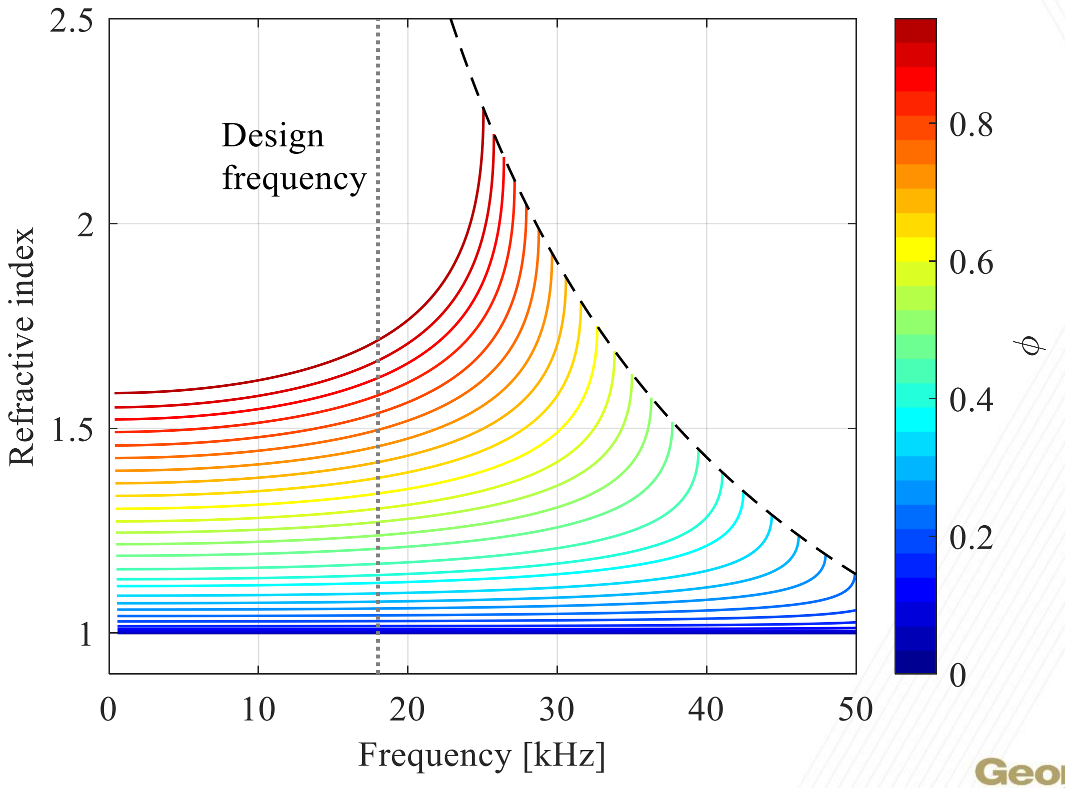
- The objective of this work is to design, analyze, and experimentally validate a 3D-printed phononic crystal lens for enhanced sound energy harvesting.

Unit Cell Design

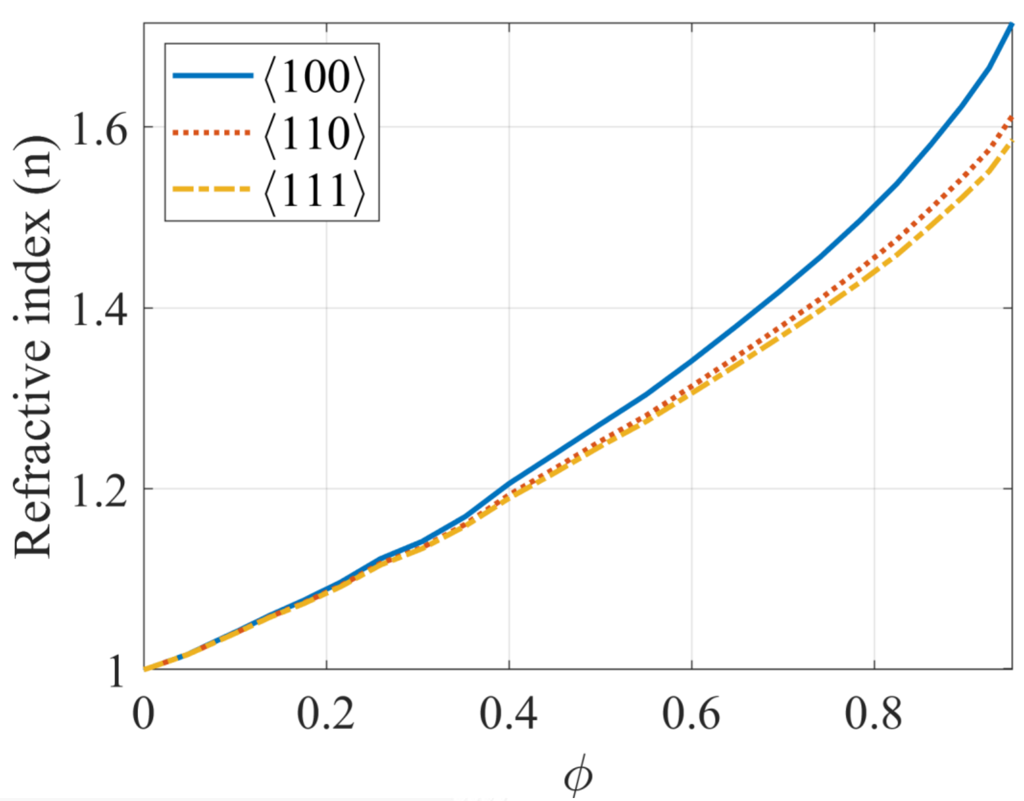
- The filling fraction ϕ controls the effective refractive index of the cell.

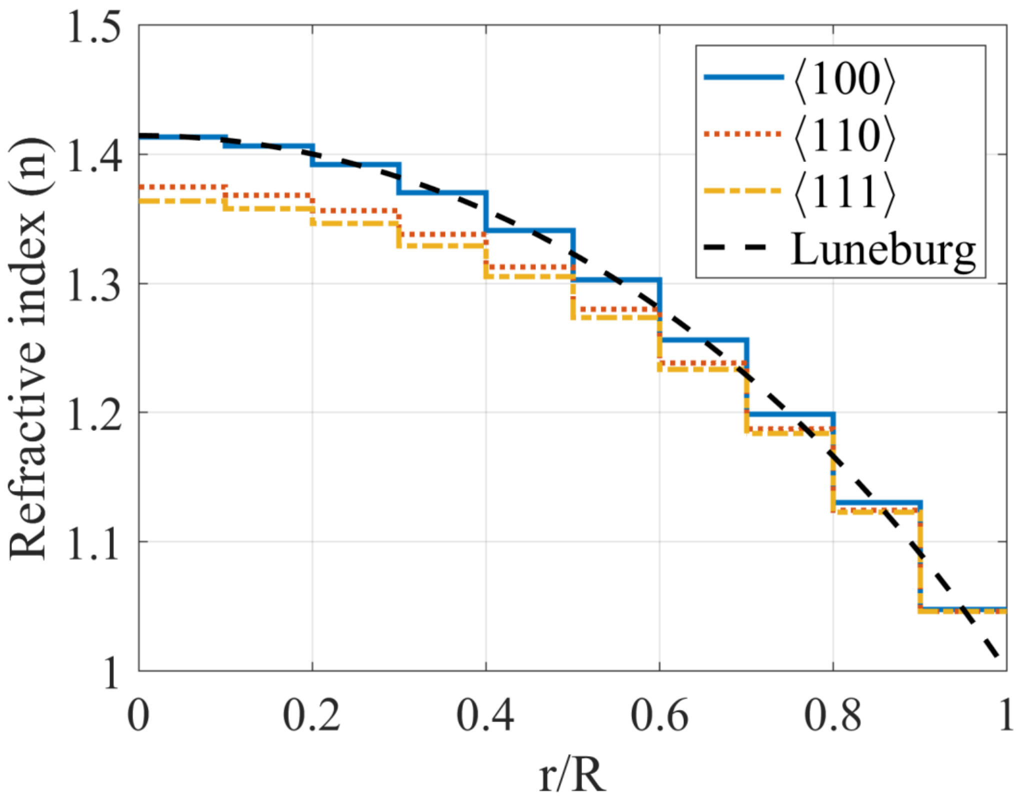
$$\phi = \frac{3ah^2 - 2h^3}{a^3}, \qquad a = 3\text{ mm}$$

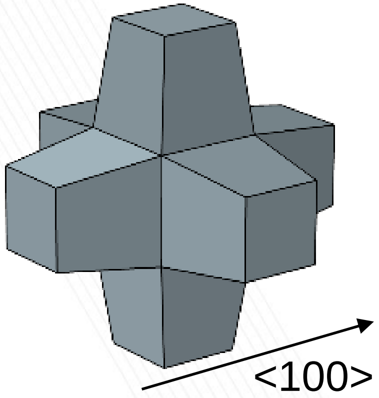




GRIN-PC Design

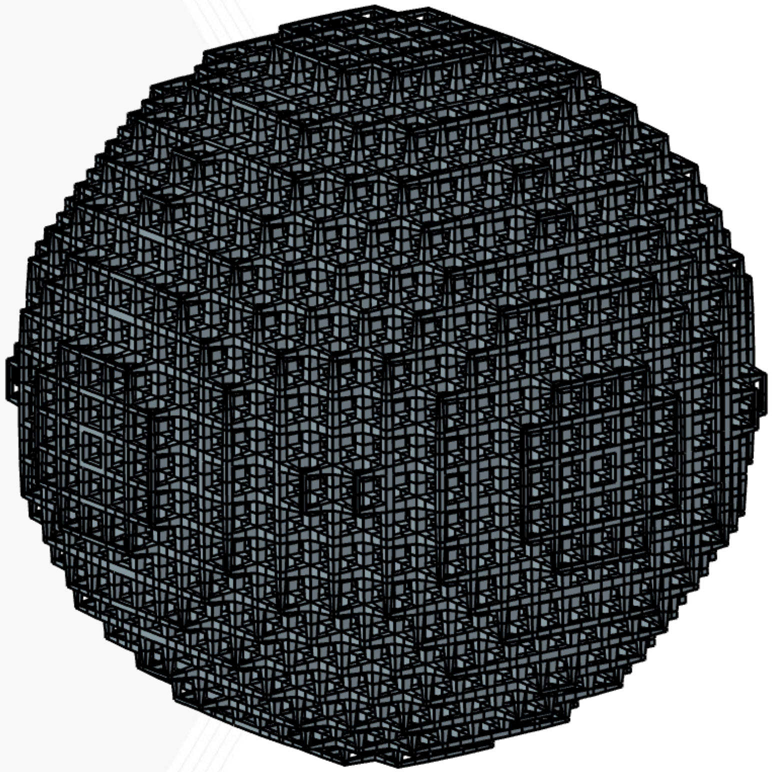




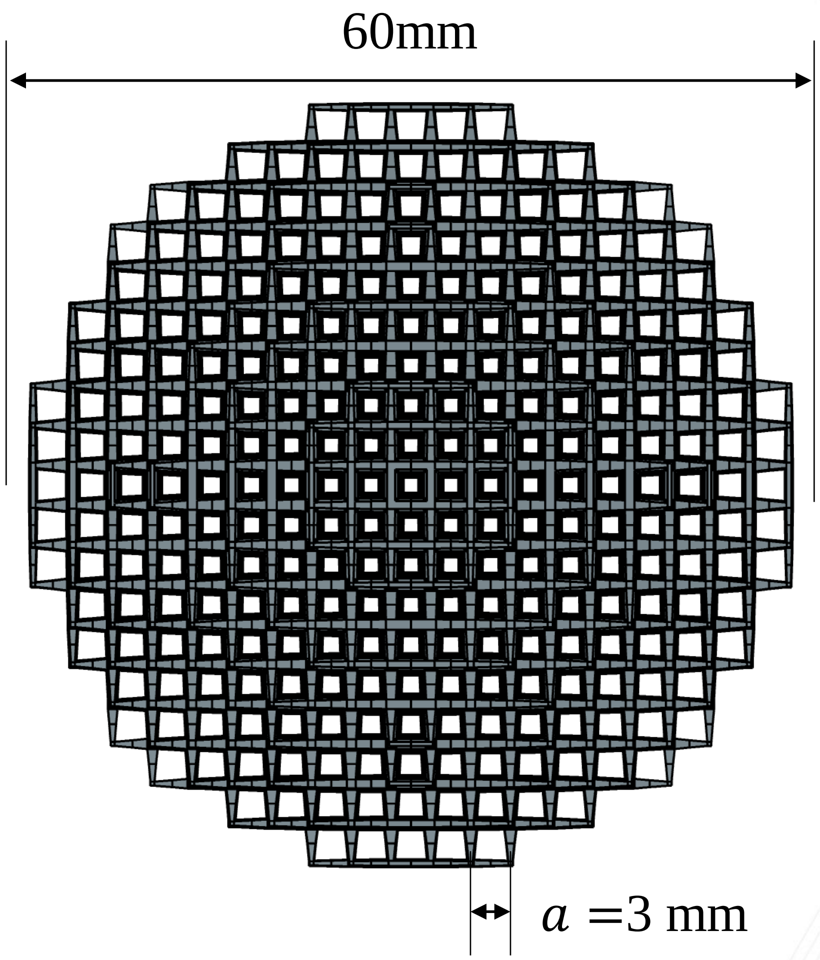


- The GRIN-PC lens is designed based on Luneburg lens profile: $n(r) = \sqrt{2 - (r/R)^2}$
- The lens implementation deviates from Luneburg profile due to unit cell anisotropy.

Designed GRIN-PC Lens



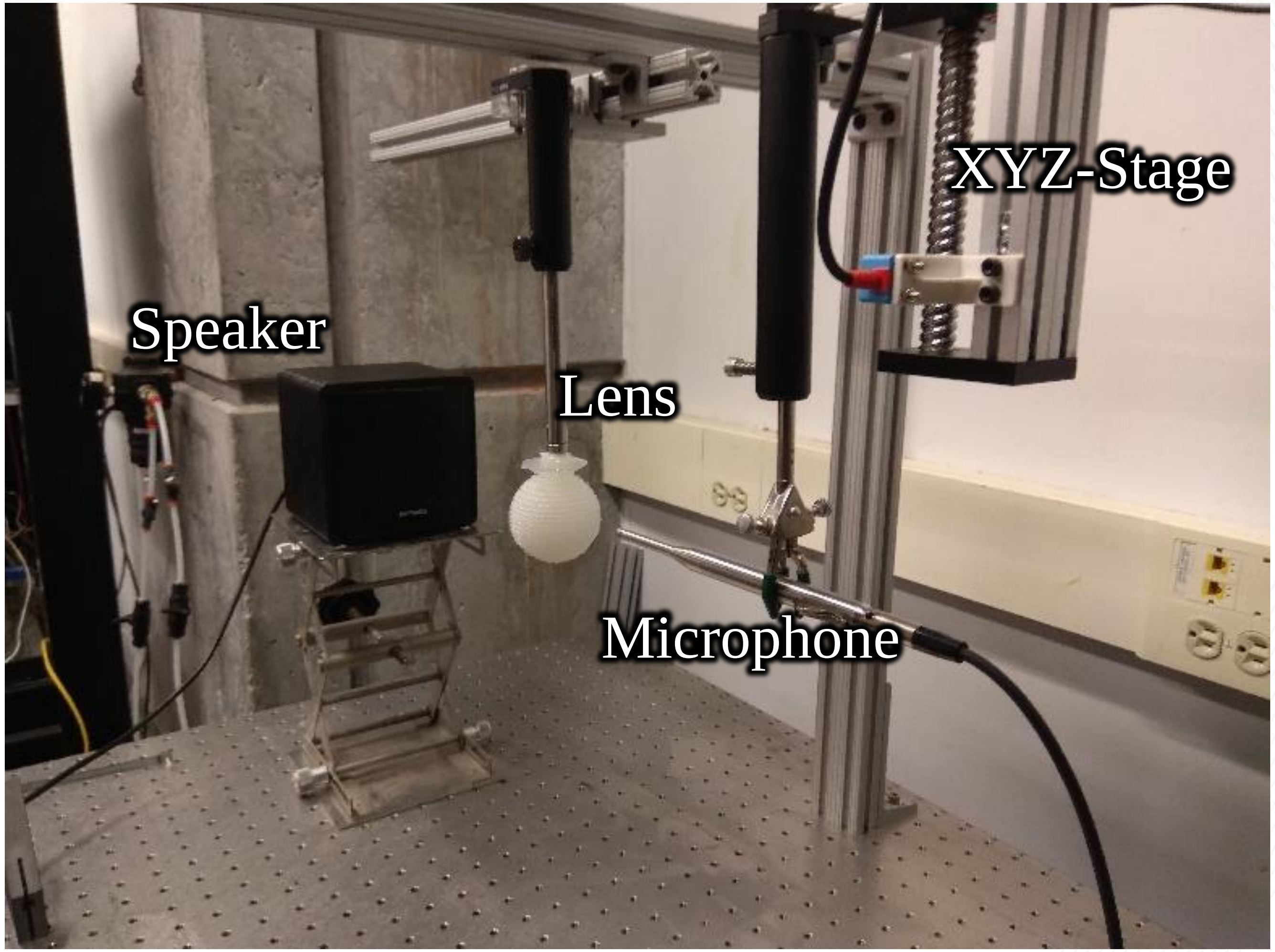
3D view



Side view

Experimental Evaluation of the Pressure Field

- A scanning microphone setup is used to map the pressure field near the focal point of the lens.
- A speaker was excited with a Gaussian sinusoidal pulse centered at 18.5 kHz and the acoustic pressure is mapped using a microphone mounted on an XYZ-stage.



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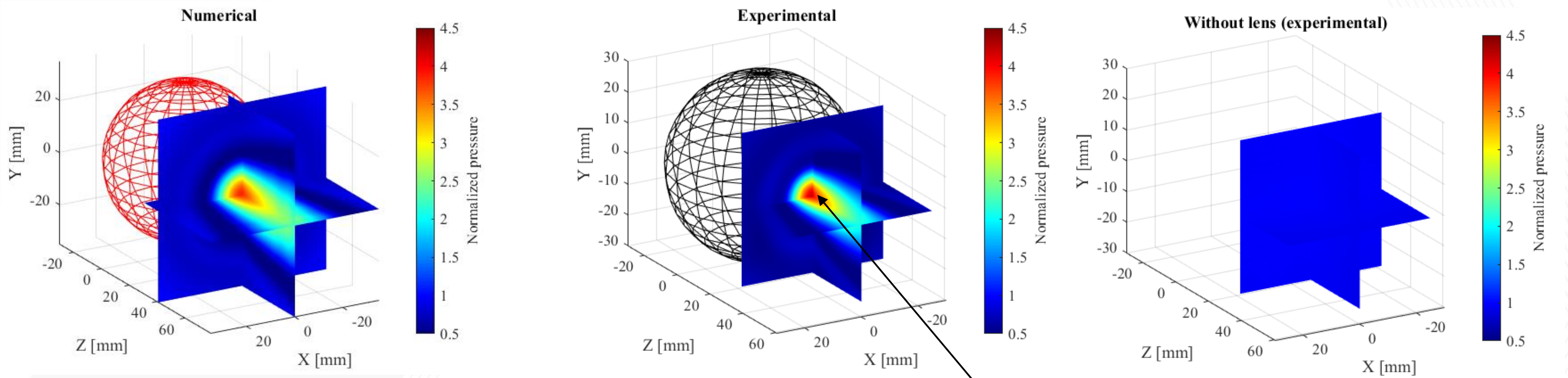
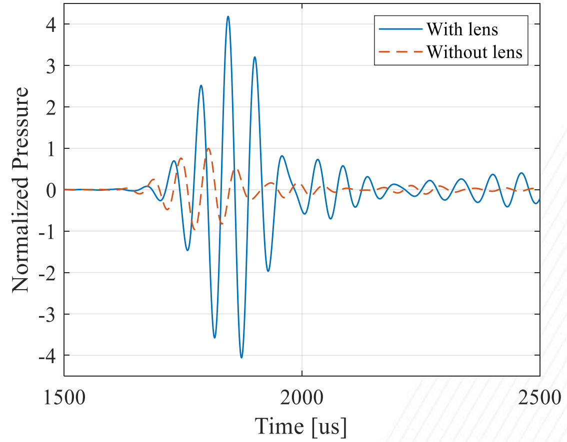
Results: 3D Pressure Field



- The normalized peak pressure field is plotted.
- A peak pressure gain of 4.4 is observed at the focal point.



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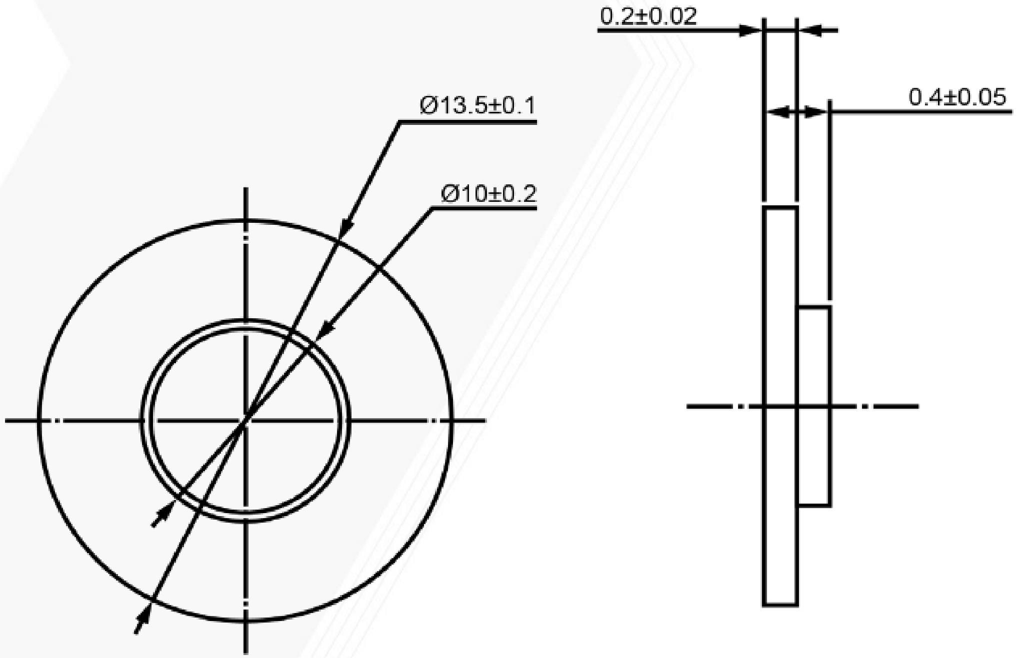
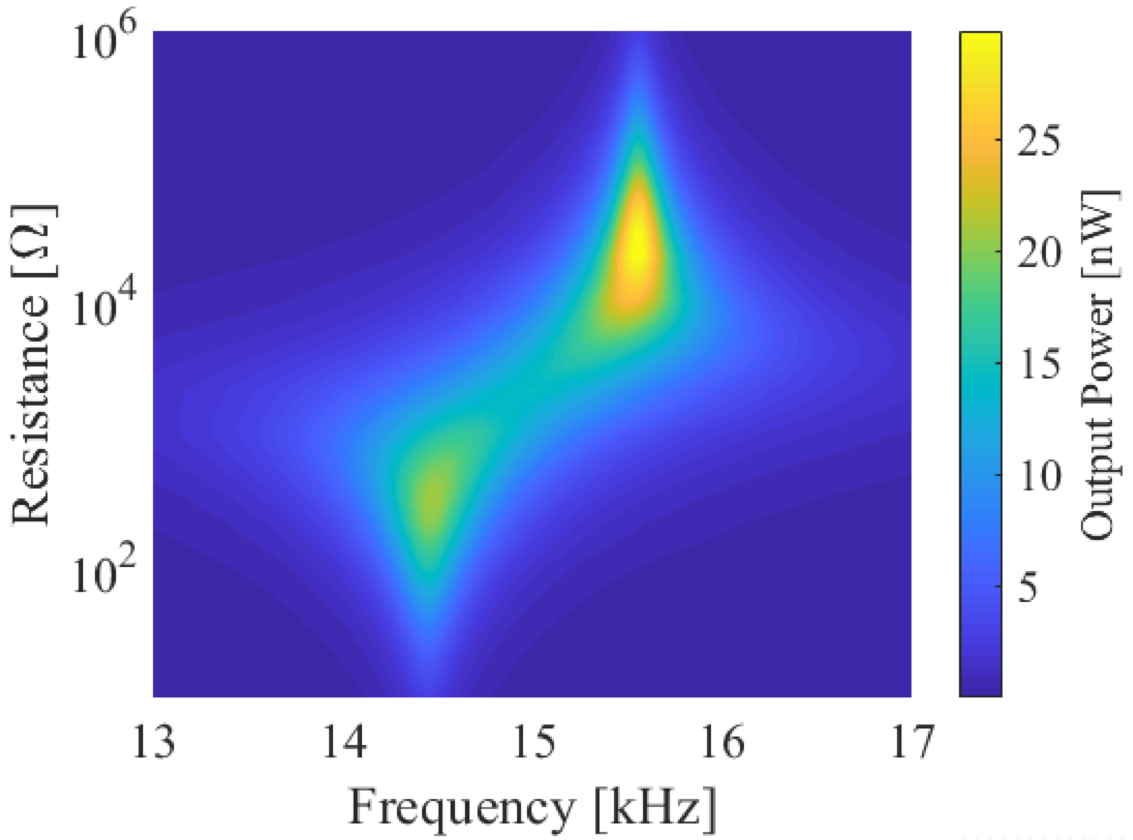
Unimorph Piezoelectric Energy Harvester

- The harvester is an off-the-shelf unimorph with a resonant frequency: 14.5 - 15.5 kHz
- The harvester is selected to be close to half wavelength of incident acoustic waves (λ = 20 mm – 25 mm)

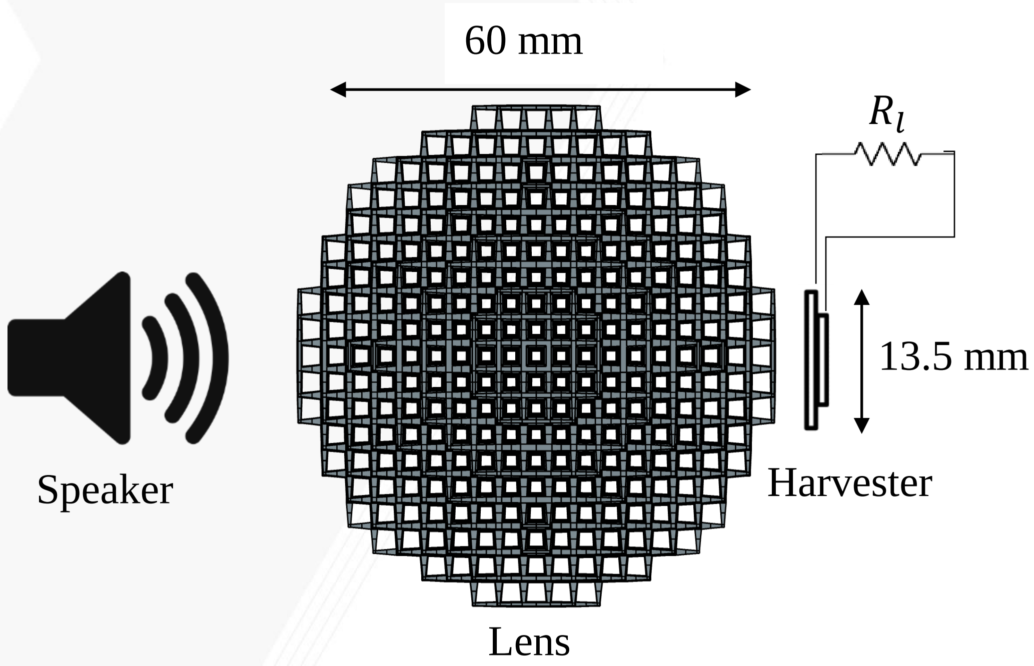


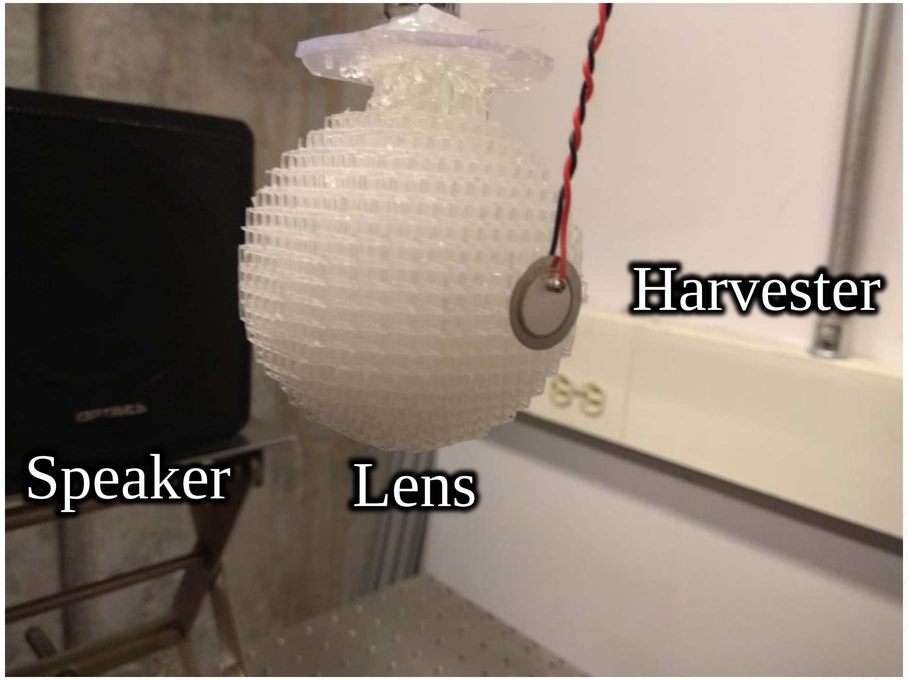


Electric power output for a 10 Pa uniform pressure excitation applied to the harvester.

Energy Harvesting Experimental Setup

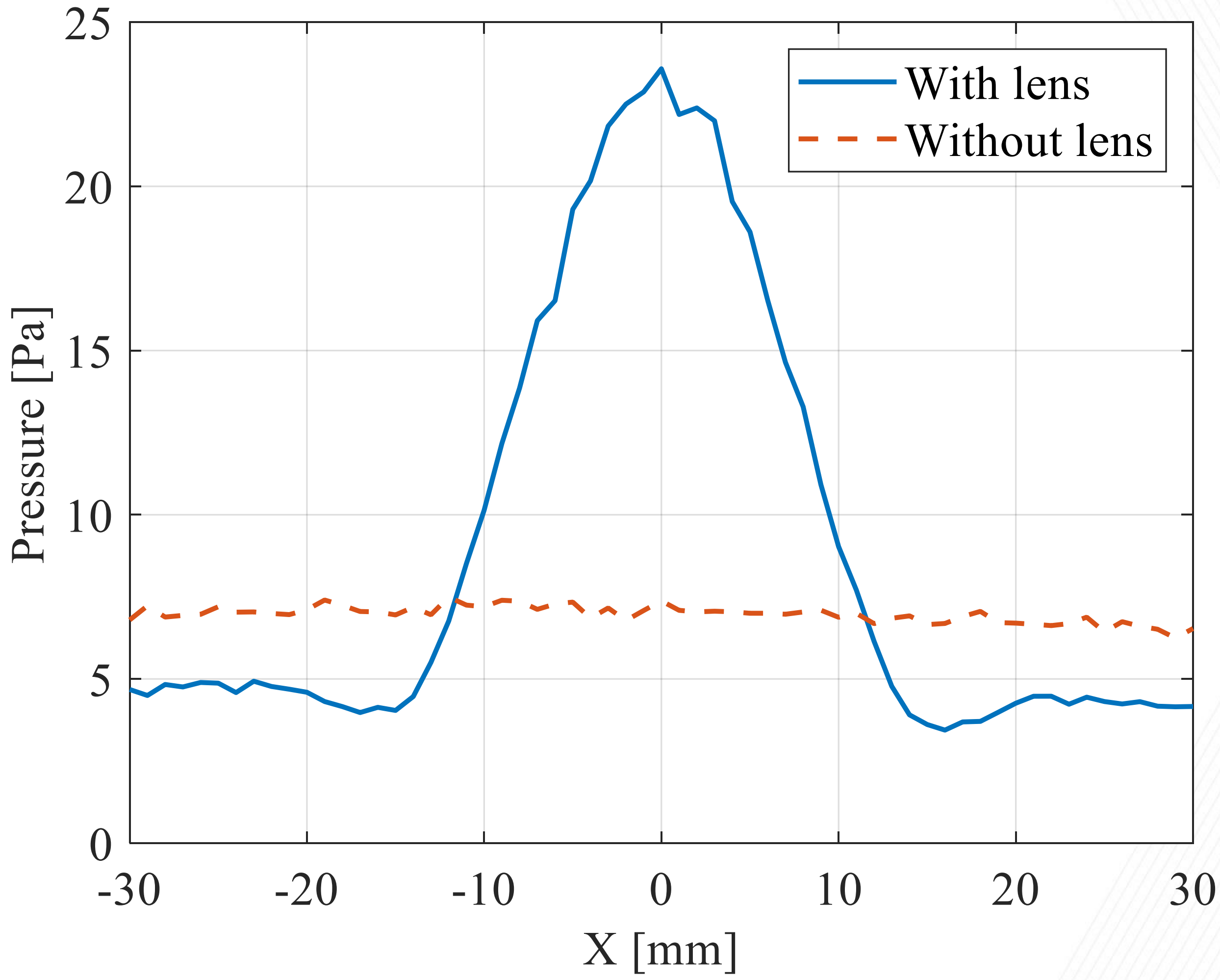
- The harvester is placed at the focal spot of the lens to estimate the output power enhancement.
- The load resistance (R_l) is varied to verify the optimal resistive loading.





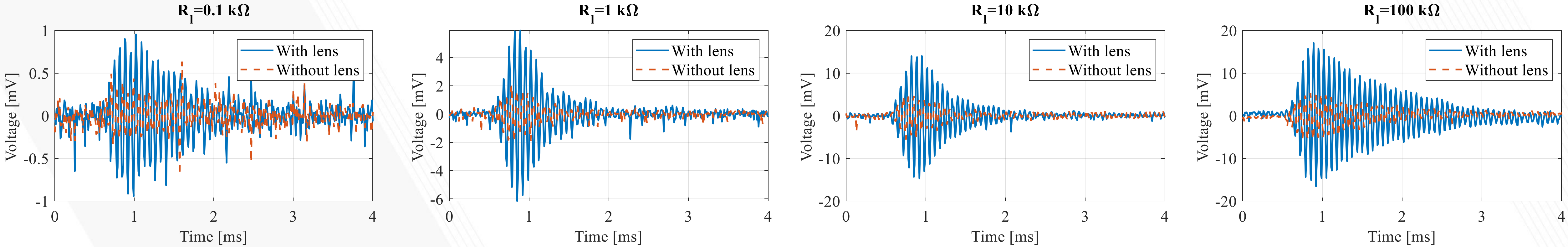
Pressure Field Without the Harvester

- An incident pressure pulse at 14.5 kHz with 4 kHz bandwidth (approximately a 4 cycles pulse) is used to excite the harvester.
- The pressure amplitude of the incident pulse is around 111 dB (7.1 Pa) in the absence of the lens.
- A pressure gain of 3.3 is observed at this frequency.

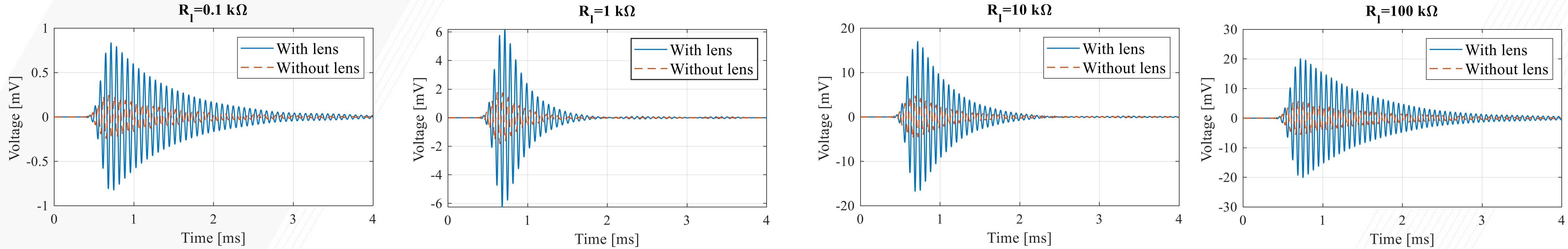


Output Voltage Signal (Time Domain)

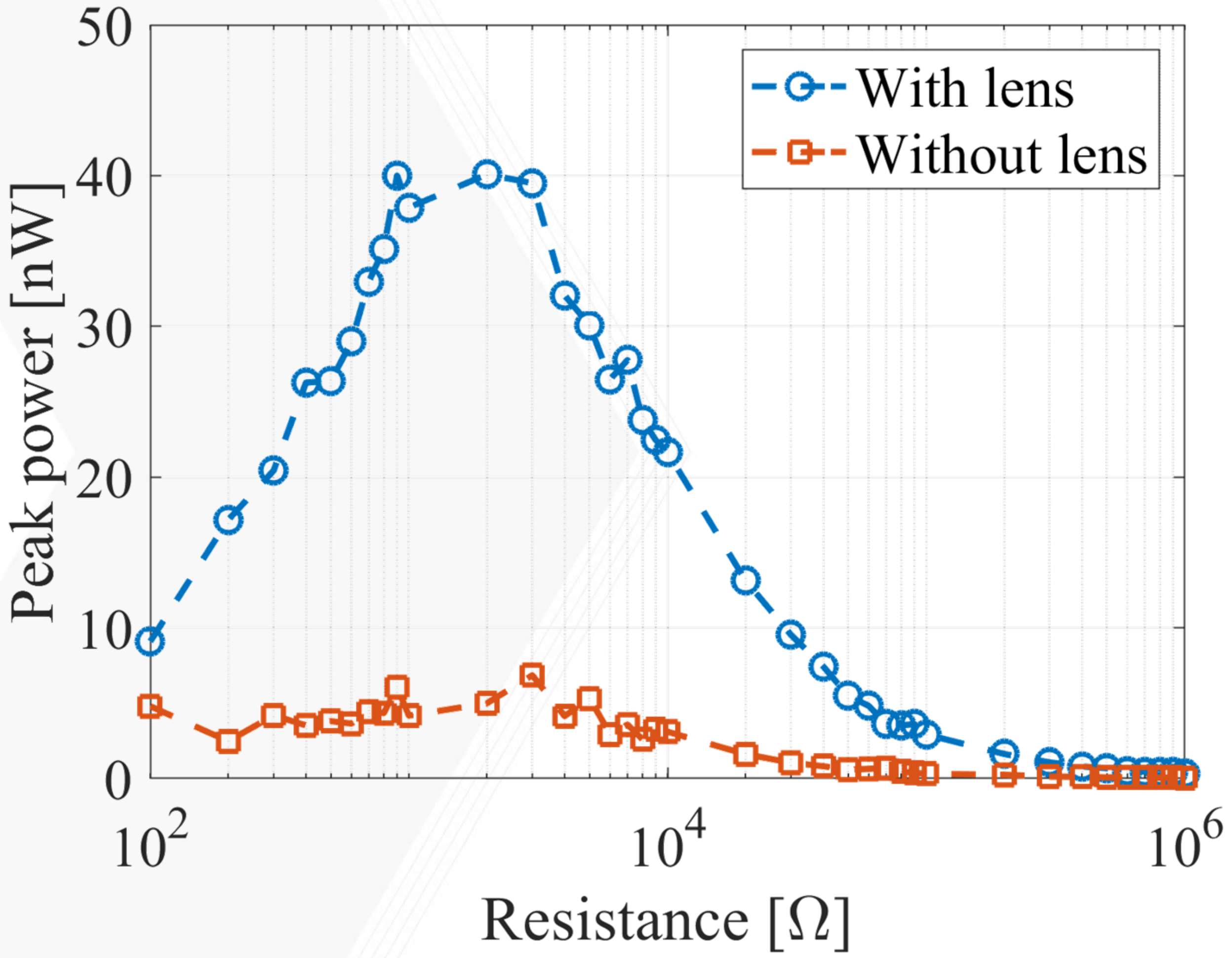
Experimental



Numerical



Power Enhancement



- An output electrical power gain of 10 is observed due to the presence of the lens.
- An optimal load resistance of 1-2 kΩ is observed which matches the numerical predictions.

Conclusions

- A 3D phononic crystal lens was designed and 3D-printed to focus sound waves (i.e. audio frequency acoustic waves) in air.
- The lens was analyzed and experimentally tested to focus broadband incident sound waves on a piezoelectric energy harvester.
- An order of magnitude increase in the power output of the harvester was observed when the lens was used (as compared to the baseline case w/o the lens).

Acknowledgment

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