

Micro-Optomechanical Acoustic Velocity Sensor

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Primary CNF Tools Used: Nanoscribe Photonic Professional GT2 Two-photon Lithography System

Abstract:

This project aims to develop an ultrasensitive, low-noise micro-optomechanical acoustic velocity sensor for detecting acoustic particle velocity in confined spaces. Existing acoustic systems predominantly measure scalar sound pressure and therefore provide limited directional information. Acoustic particle-velocity sensing enables vector detection, but achieving a high signal-to-noise ratio in a miniaturized device remains challenging. To address this challenge, our sensor integrates a spider-web-inspired, velocity-sensitive 2D microstructure with a fiber-based Fabry–Pérot interferometric readout. The device incorporates three key innovations: a bio-inspired structure with high responsivity to acoustic particle velocity, damping-enhanced suppression of thermomechanical noise, and compact fiber-optic transduction for ultrasensitive displacement readout. The device achieves a peak sensitivity of 0.5 V/Pa at 2.4 kHz and an average minimum detectable equivalent pressure of 7×10^{-5} Pa/ $\sqrt{\text{Hz}}$ over the frequency range from 100 Hz to 20 kHz. Building on these results, our current work at the Cornell NanoScale Facility explores mosquito-inspired three-dimensional microscale structures fabricated using two-photon lithography to further enhance damping and reduce thermomechanical noise.

Research Summary:

Existing acoustic sensors primarily detect sound pressure, a scalar quantity that lacks inherent directional information. Acoustic particle-velocity sensing can directly provide vector information [1,2]; however, achieving miniaturized devices with high sensitivity and low noise floors remains challenging. To address this gap, we developed an ultrasensitive, low-noise micro-optomechanical acoustic vector sensor for detecting weak particle velocity in confined spaces [3].

The micro-optomechanical sensor combines three key features: a spider-web-inspired sensing structure that

provides high mechanical responsivity to acoustic particle velocity, deliberately enhanced viscous damping that reduces thermomechanical noise [4], and a fiber-based interferometer that enables ultrasensitive displacement readout. The sensor operates by positioning a velocity-sensitive microstructure near the end of an optical fiber to form a Fabry–Pérot cavity. Reflections from the movable microstructure and the fiber end interfere within the cavity. Acoustic particle motion interacts viscously with the microstructure and induces mechanical displacement, which changes the cavity length and modulates the reflected optical intensity. The modulated optical signal is then detected by a photodetector, providing a compact and ultrasensitive means of converting weak acoustic motion into an electrical signal through optical transduction.

Figure 1 presents the fabricated sensing structures, the microfabrication process, and the assembled sensor. The silicon nitride sensing structures shown in Figure 1A were fabricated through five main steps, as illustrated in Figure 1B: thin-film deposition, photolithographic patterning, etching, structural release, and drying. These processes produced suspended velocity-sensitive microstructures. The silicon nitride thin film was deposited at the Cornell NanoScale Facility using low-pressure chemical vapor deposition. Figure 1C shows the assembled sensor.

Figure 2 shows the measured acoustic performance. The optically measured sensitivity closely agrees with the independently measured mechanical sensitivity obtained using a laser Doppler vibrometer. The sensor reached a peak velocity sensitivity of approximately 208 V/(m/s), corresponding to an equivalent pressure sensitivity of approximately 0.5 V/Pa near the mechanical resonance at 2.4 kHz. Owing to the enhanced viscous damping of the mesh structure [4], the sensor achieved an average minimum detectable pressure of approximately 7×10^{-5} Pa/ $\sqrt{\text{Hz}}$ over the frequency range from 100 Hz to 20 kHz.

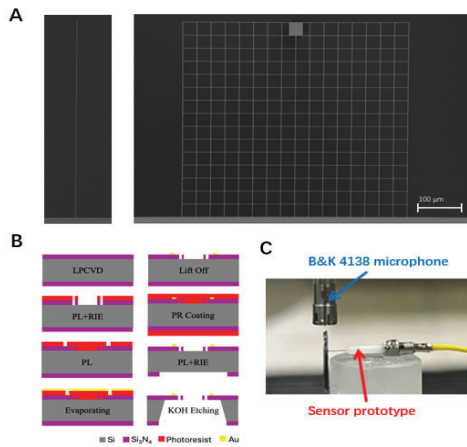


Figure 1: Sensor fabrication and assembly. (A) SEM images of the velocity-sensitive microstructures. The 1D cantilever has dimensions of $500\ \mu\text{m} \times 2\ \mu\text{m} \times 780\ \text{nm}$, while the 2D mesh has overall dimensions of $500\ \mu\text{m} \times 500\ \mu\text{m} \times 780\ \text{nm}$ and consists of $2\text{-}\mu\text{m}$ -wide beams separated by $30\text{-}\mu\text{m}$ gaps. (B) Microfabrication process. (C) Sensor prototype. A B&K 4138 microphone is placed nearby as an acoustic reference.

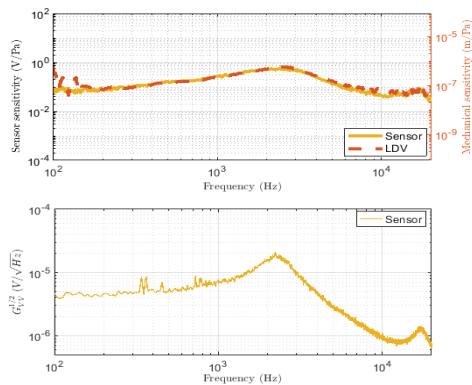


Figure 2: Sensor performance. (A) Sound-induced velocity response, showing close agreement between the sensor and a laser Doppler vibrometer (LDV). (B) Sensor noise floor, dominated by the thermomechanical motion of the 2D micromesh.

To further increase damping and thereby lower the noise floor, our current work at the Cornell NanoScale Facility uses the Nanoscribe Photonic Professional GT2 two-photon lithography system to fabricate three-dimensional microscale sensing structures. The structures are printed in IP-S photoresist using a $25\times$ objective, enabling the fabrication of relatively large three-dimensional beam networks while maintaining microscale feature resolution. Figure 4 presents an example of a fabricated three-dimensional lattice. Compared with conventional microfabrication methods, two-photon lithography offers greater geometric freedom for enhancing viscous damping while preserving sufficient mechanical responsivity. These initial trials are being used to optimize the device geometry and printing parameters for future optical integration and acoustic characterization.

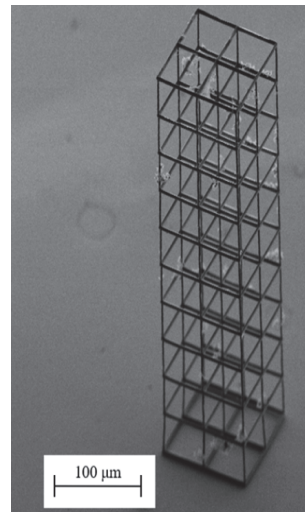


Figure 3: SEM image of a 3D lattice structure fabricated using a two-photon lithography system Nanoscribe GT2. The lattice has overall dimensions of $100\ \mu\text{m} \times 100\ \mu\text{m} \times 500\ \mu\text{m}$. Adjacent beams are spaced $50\ \mu\text{m}$ apart, and each beam has a square cross-section of $2\ \mu\text{m} \times 2\ \mu\text{m}$. The highly damped 3D lattice is designed to improve the noise performance of the velocity sensor.

Conclusions and Future Steps:

The current sensor has demonstrated highly sensitive, low-noise vector detection of acoustic particle velocity. Supported by the National Institute on Deafness and Other Communication Disorders of the National Institutes of Health (NIH/NIDCD), our future work will focus on fabricating a higher-performance particle-velocity sensor with enhanced sensitivity, reduced noise, and a sufficiently compact form factor for operation in the confined ear canal. The velocity sensor will then be integrated with a miniaturized pressure sensor to create a dual-sensing ear-canal probe capable of simultaneously measuring acoustic particle velocity and sound pressure. By providing complementary vector and scalar measurements, the probe is intended to improve the accuracy and reliability of otoacoustic-emission measurements, enable better characterization of sound propagation within the ear canal, and ultimately support earlier and more precise detection of inner-ear dysfunction and hearing loss.

References:

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