Fibre-Based Optomechanical Acoustic Sensing

L.R. McQueen[1], G.I. Harris[1], N. Bawden[1], W.P. Bowen[1]

[1]ARC Centre of Excellence for EQUS, School of Mathematics and Physics, University of Queensland, St. Lucia QLD 4072, Australia

Acoustic Sensor Applications

The University of Queensland
Australia
EQUS

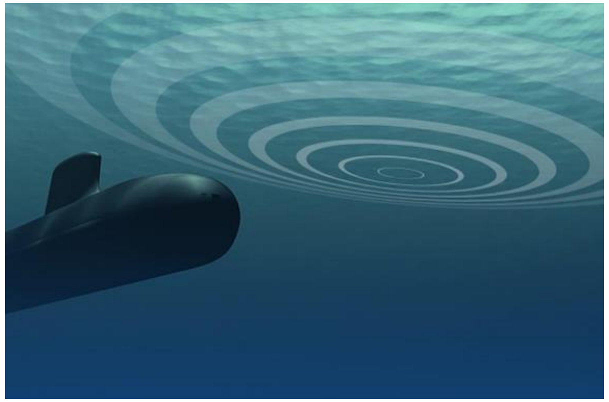
Acoustic Sensor Applications

Acoustic sensors have many real-world applications

Acoustic Sensor Applications

Acoustic sensors have many real-world applications

SONAR and microphones

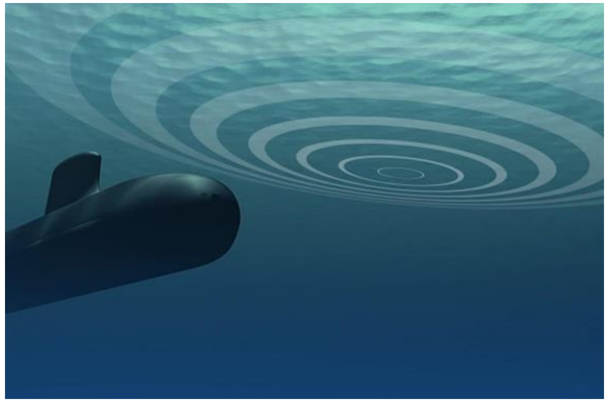


HBK (2022)

Acoustic Sensor Applications

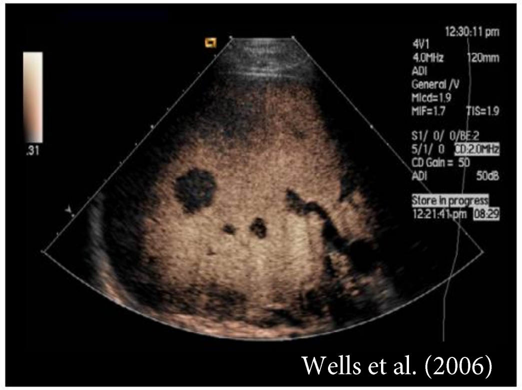
Acoustic sensors have many real-world applications

SONAR and microphones

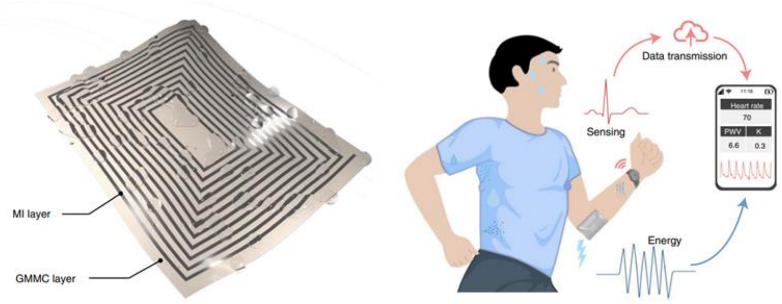


HBK (2022)

Biomedical diagnostics



Wells et al. (2006)

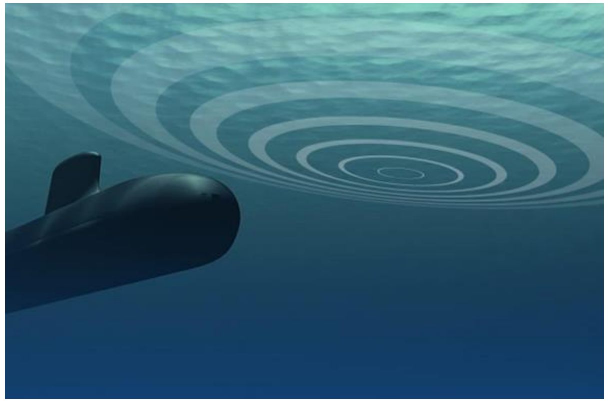


Zhou et al. (2021)

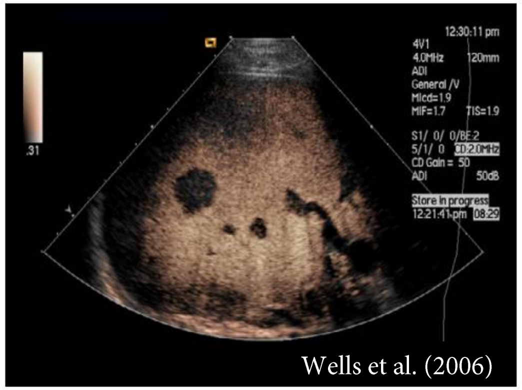
Acoustic Sensor Applications

Acoustic sensors have many real-world applications

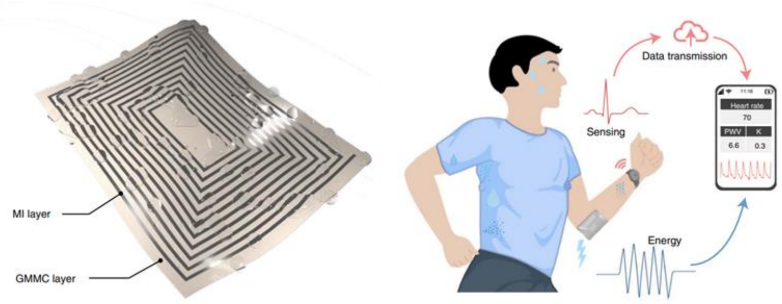
SONAR and microphones



HBK (2022)



Wells et al. (2006)



Zhou et al. (2021)

Biomedical diagnostics

However, most commercially available sensors are **limited by size (resolution)** and **electric noise (sensitivity)**

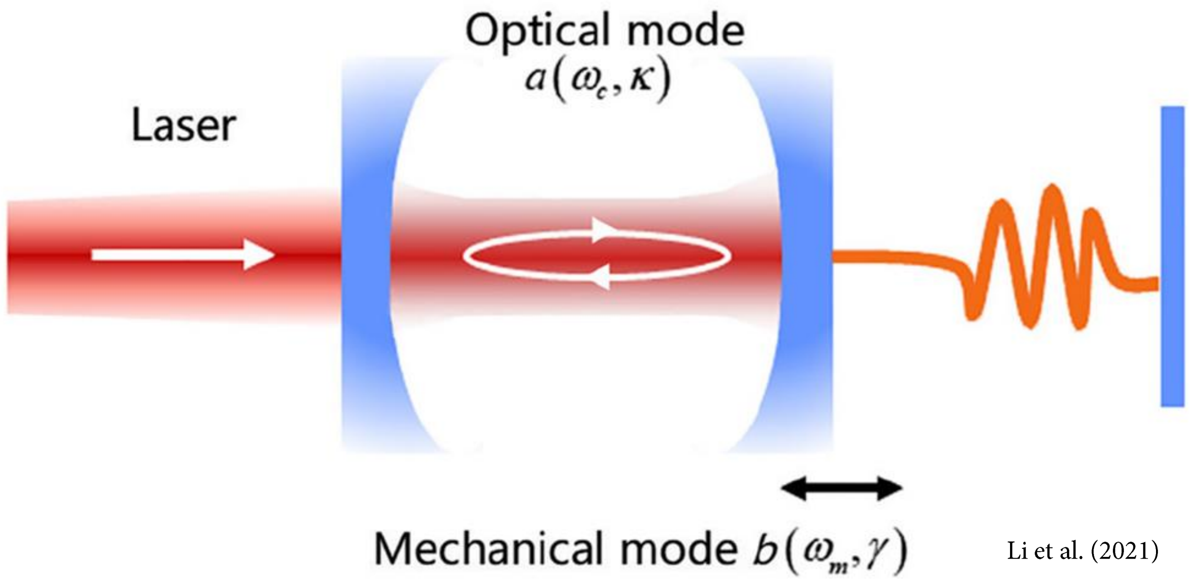
Optomechanical Sensing

Optomechanical Sensing

Cavity optomechanical ultrasound sensing involves using dual optical and mechanical resonances to enhance the ultrasound signal

Optomechanical Sensing

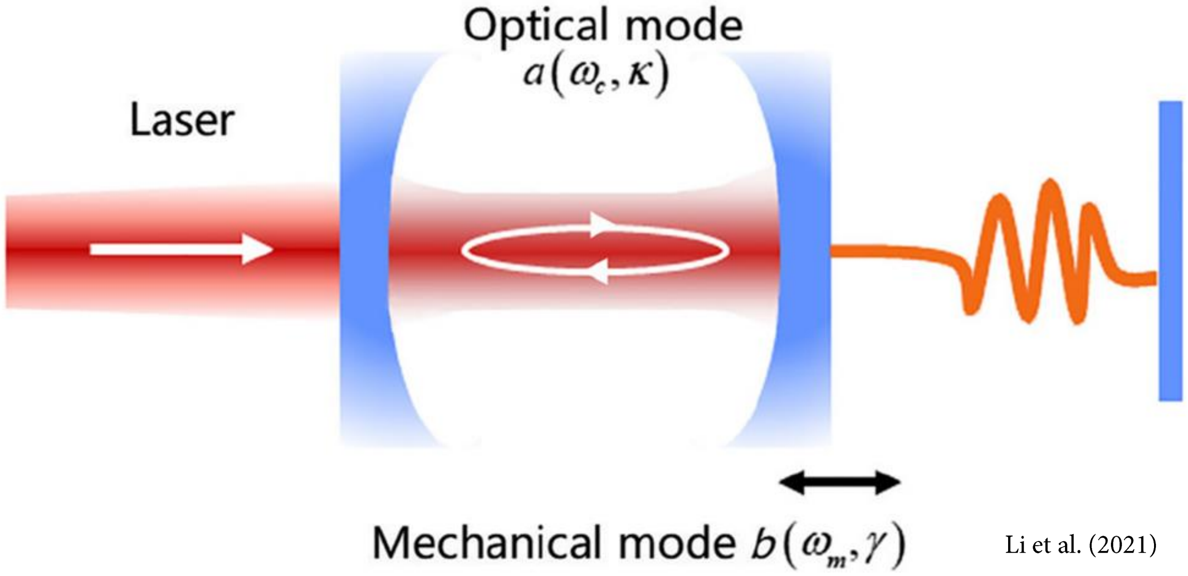
Cavity optomechanical ultrasound sensing involves using dual optical and mechanical resonances to enhance the ultrasound signal



Li et al. (2021)

Optomechanical Sensing

Cavity optomechanical ultrasound sensing involves using dual optical and mechanical resonances to enhance the ultrasound signal



Li et al. (2021)

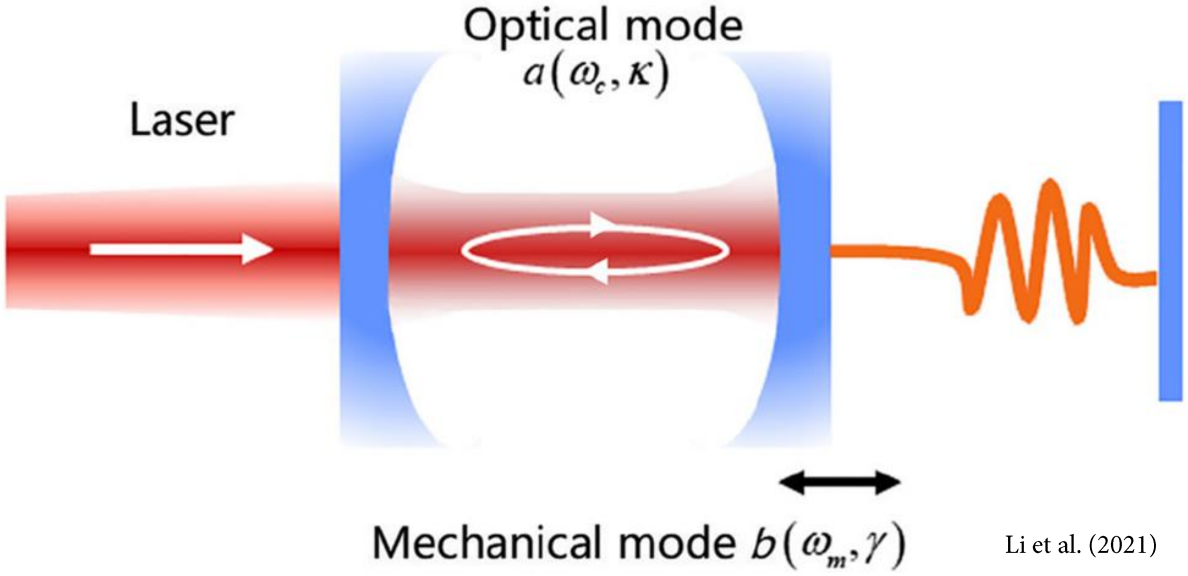
Basic dynamics modelled with Hamiltonian

$$H = H_{\text{drive}} + H_{\text{free}} + H_{\text{int}}$$

- H_{drive}: Optical driving of system
- H_{free}: Uncoupled optical and mechanical modes
- $H_{\text{int}} = g_0 \hat{a}^\dagger \hat{a} \hat{x}$: Optomechanical interaction between optical and mechanical modes

Optomechanical Sensing

Cavity optomechanical ultrasound sensing involves using dual optical and mechanical resonances to enhance the ultrasound signal



Li et al. (2021)

Basic dynamics modelled with Hamiltonian

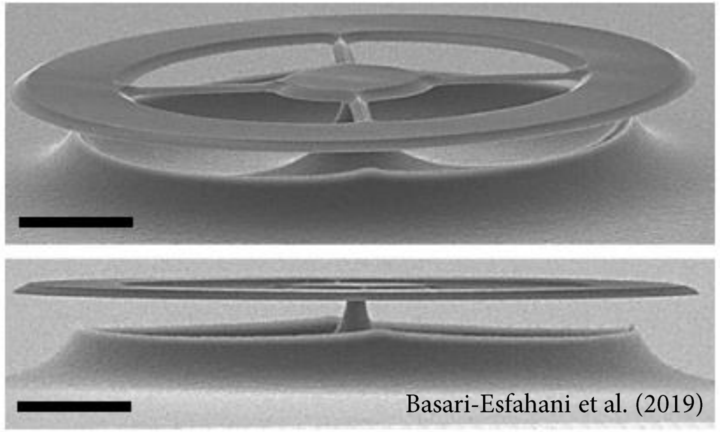
$$H = H_{\text{drive}} + H_{\text{free}} + H_{\text{int}}$$

- H_{drive}: Optical driving of system
- H_{free}: Uncoupled optical and mechanical modes
- $H_{\text{int}} = g_0 \hat{a}^\dagger \hat{a} \hat{x}$: Optomechanical interaction between optical and mechanical modes

This approach should result in **improved sensitivity**, and potentially **enable both miniaturisation and increased spatial resolution** of the ultrasound sensors

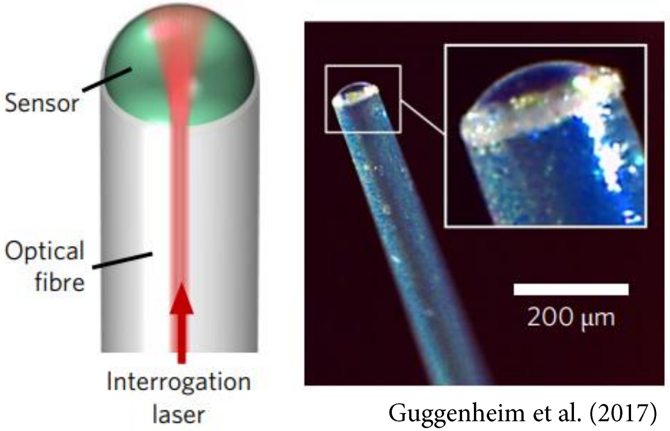
Optomechanical Acoustic Sensing

Optomechanical Acoustic Sensing



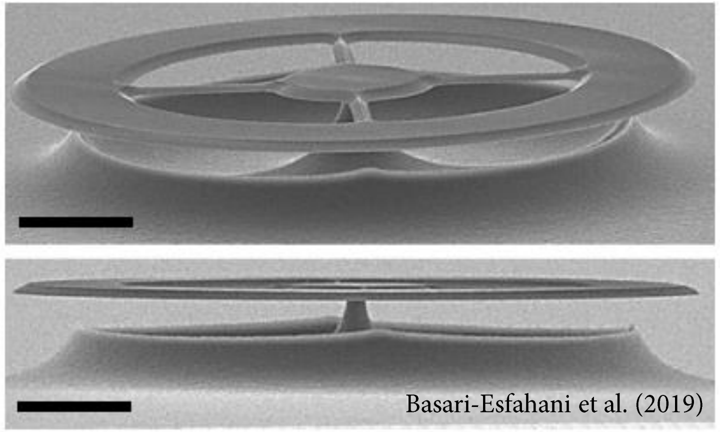
Basari-Esfahani et al. (2019)

Significant milestones in sensitivity achieved, but **limited by robustness** and can be **difficult to mass produce**



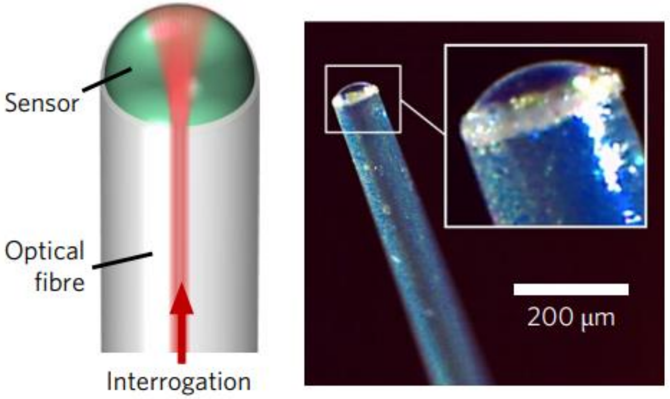
Guggenheim et al. (2017)

Optomechanical Acoustic Sensing



Basari-Esfahani et al. (2019)

Significant milestones in sensitivity achieved, but **limited by robustness** and can be **difficult to mass produce**



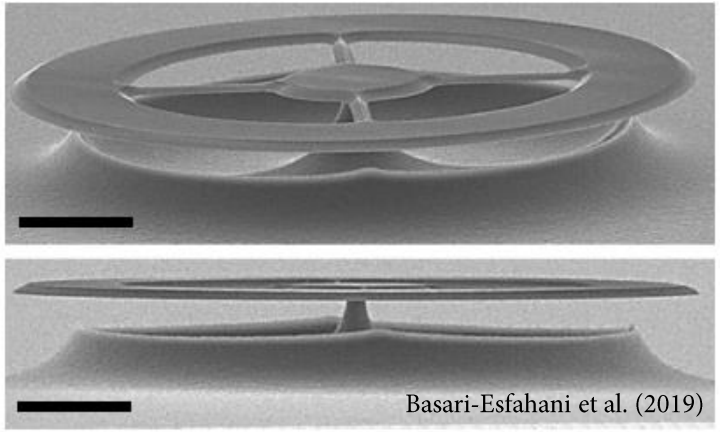
Guggenheim et al. (2017)

Silicon-related technology has evolved with the semiconductor industry

↓

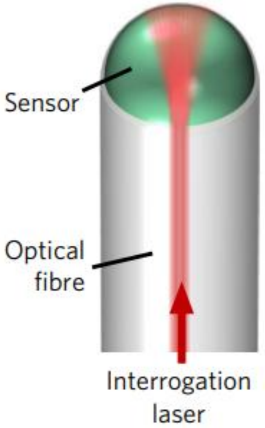
Silicon micro-resonators can be easily fabricated on chip and silicon-on-insulator (SOI) wafers can be massively produced

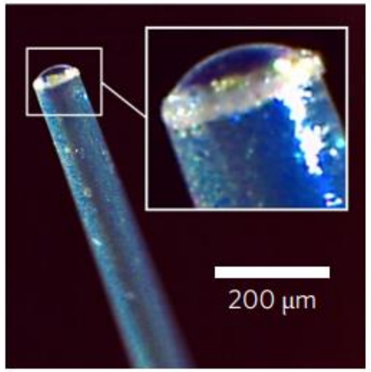
Optomechanical Acoustic Sensing



Basari-Esfahani et al. (2019)

Significant milestones in sensitivity achieved, but **limited by robustness** and can be **difficult to mass produce**



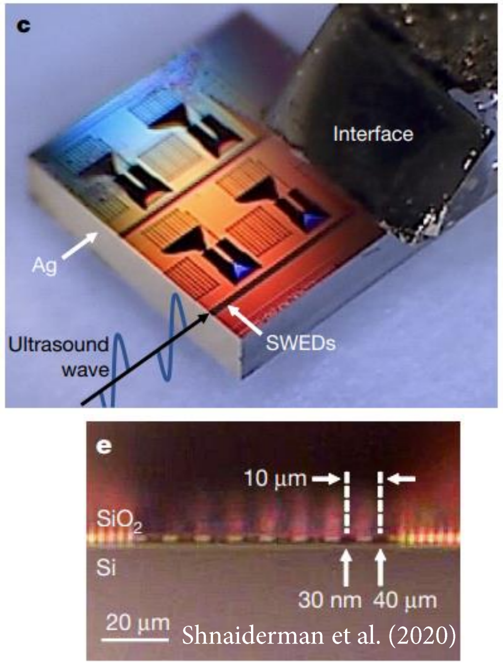


Guggenheim et al. (2017)

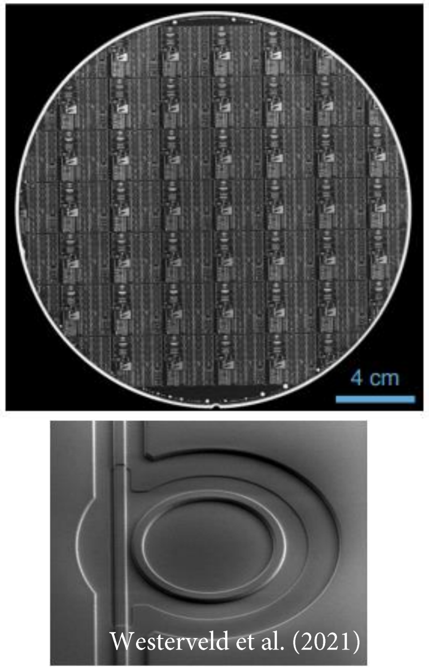
Silicon-related technology has evolved with the semiconductor industry

↓

Silicon micro-resonators can be easily fabricated on chip and silicon-on-insulator (SOI) wafers can be massively produced

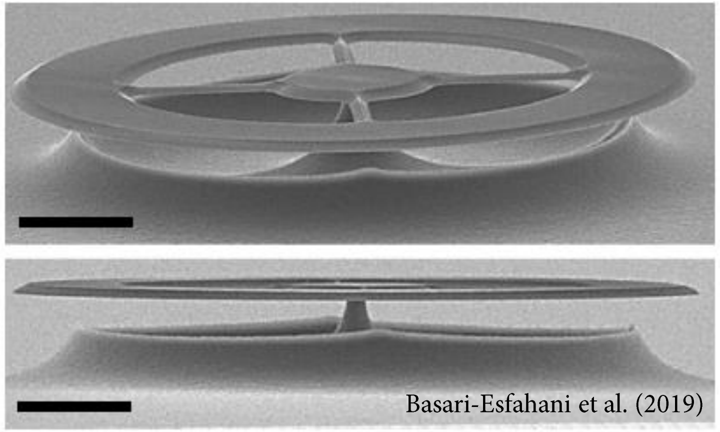


Shnaiderman et al. (2020)



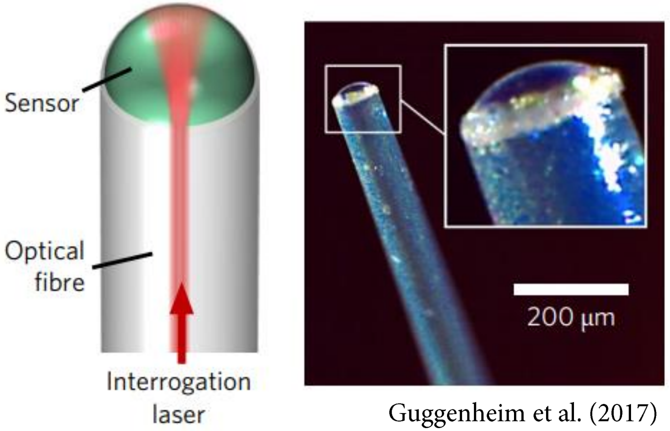
Westerveld et al. (2021)

Optomechanical Acoustic Sensing



Basari-Esfahani et al. (2019)

Significant milestones in sensitivity achieved, but **limited by robustness** and can be **difficult to mass produce**

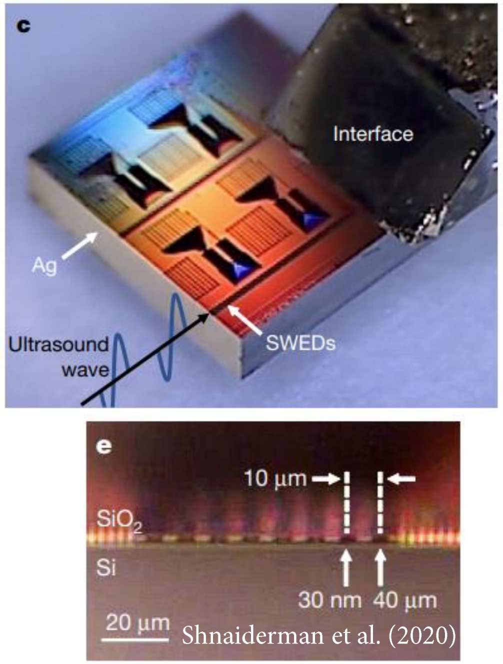


Guggenheim et al. (2017)

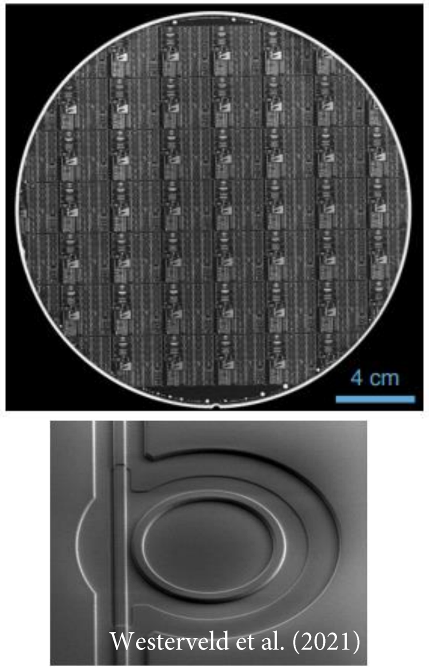
Silicon-related technology has evolved with the semiconductor industry

↓

Silicon micro-resonators can be easily fabricated on chip and silicon-on-insulator (SOI) wafers can be massively produced



Shnaiderman et al. (2020)



Westerveld et al. (2021)

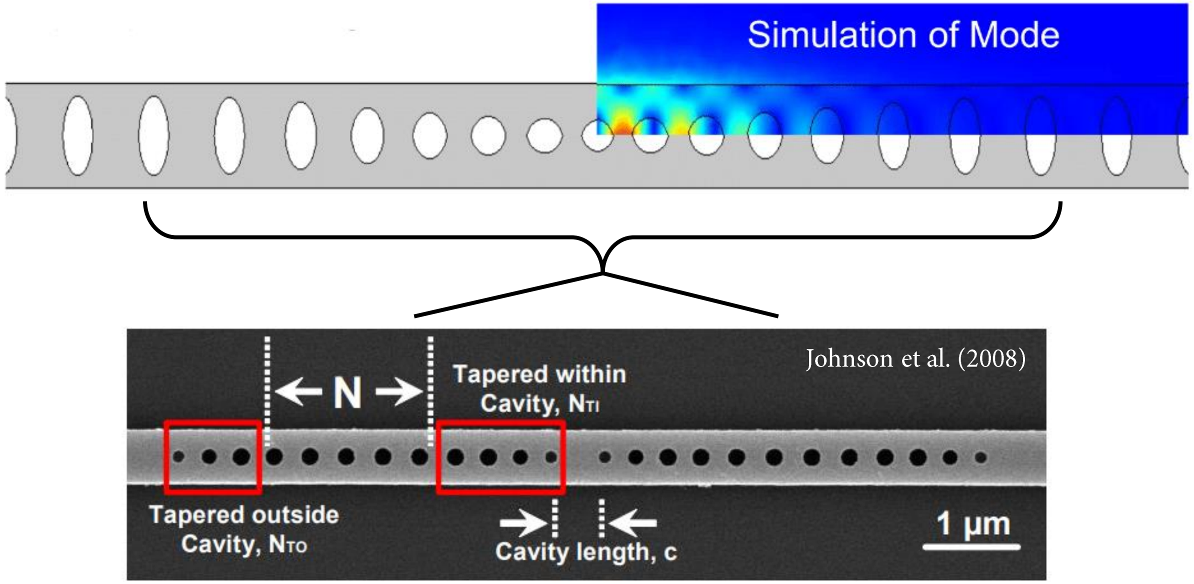
However, can be **limited by sensitivity** and **robustness**

Concept and Architecture

- We develop and demonstrate **acoustic sensing using a nanometre-sized acoustic sensor based on 1D photonic crystals (PhC)**

Concept and Architecture

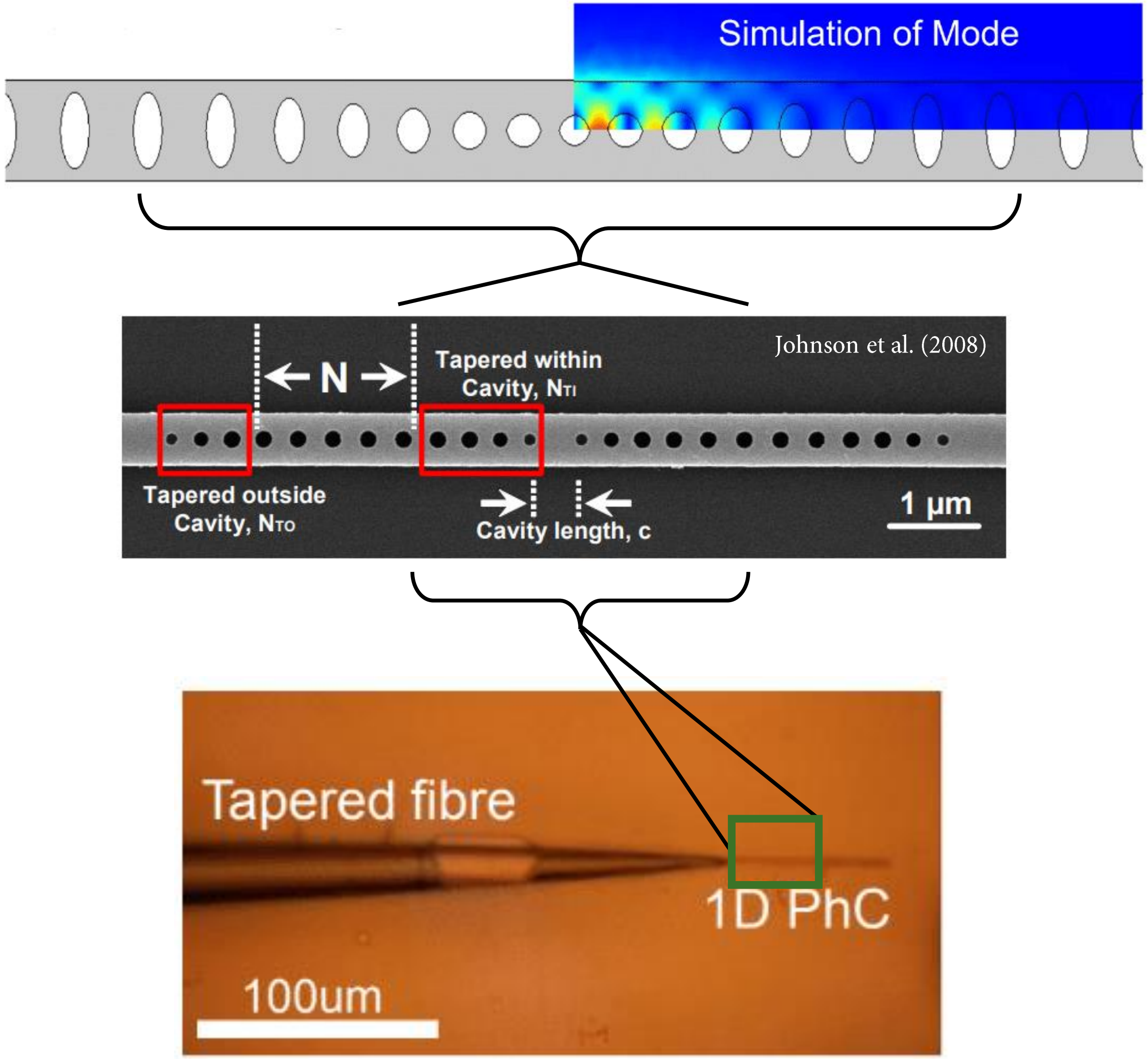
- We develop and demonstrate acoustic sensing using a nanometre-sized acoustic sensor based on 1D photonic crystals (PhC)



Concept and Architecture

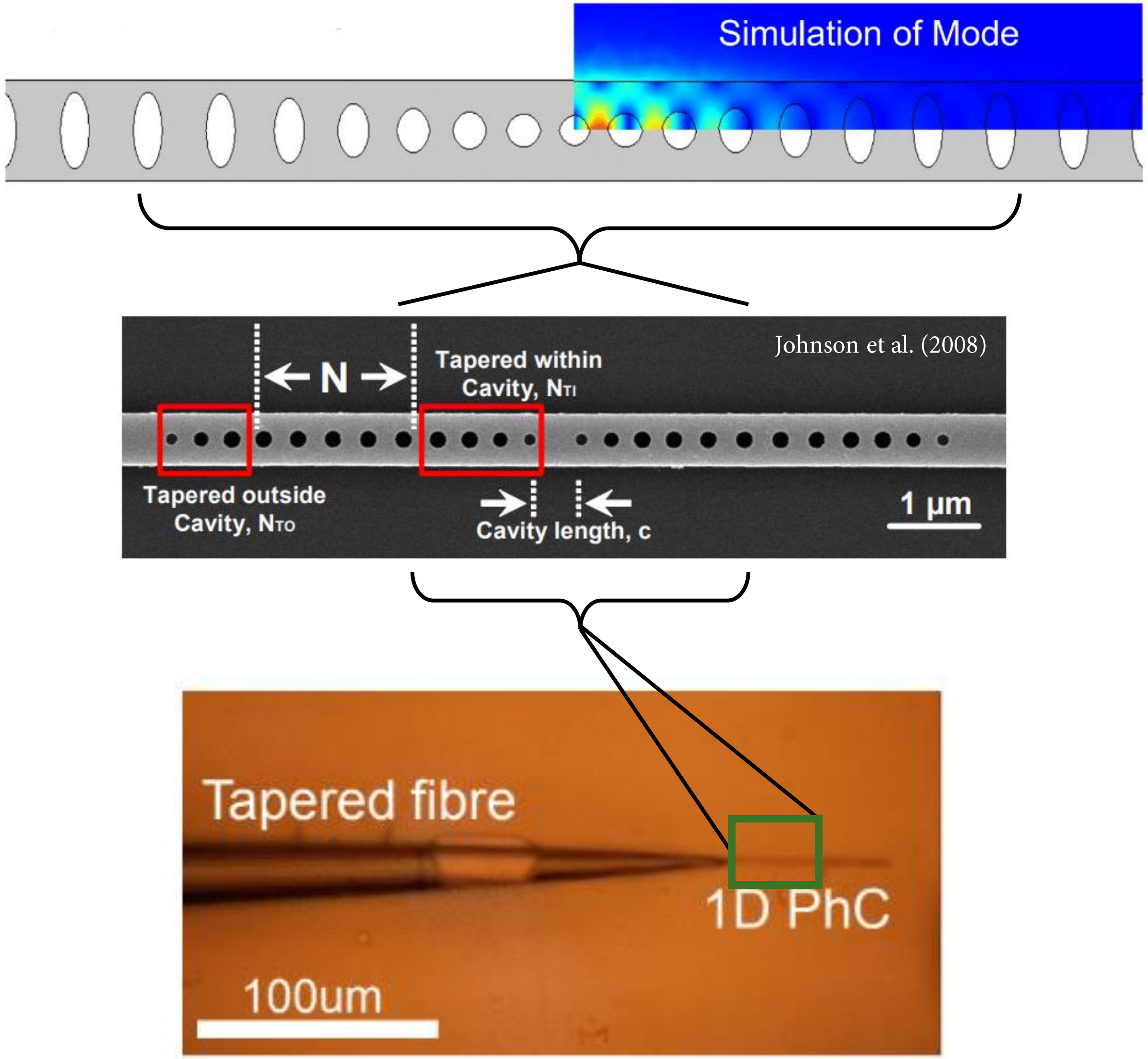
- We develop and demonstrate **acoustic sensing using a nanometre-sized acoustic sensor based on 1D photonic crystals (PhC)**

- Light is coupled into the device waveguide, and the resonant wavelength is trapped in the PhC defect "cavity"



Concept and Architecture

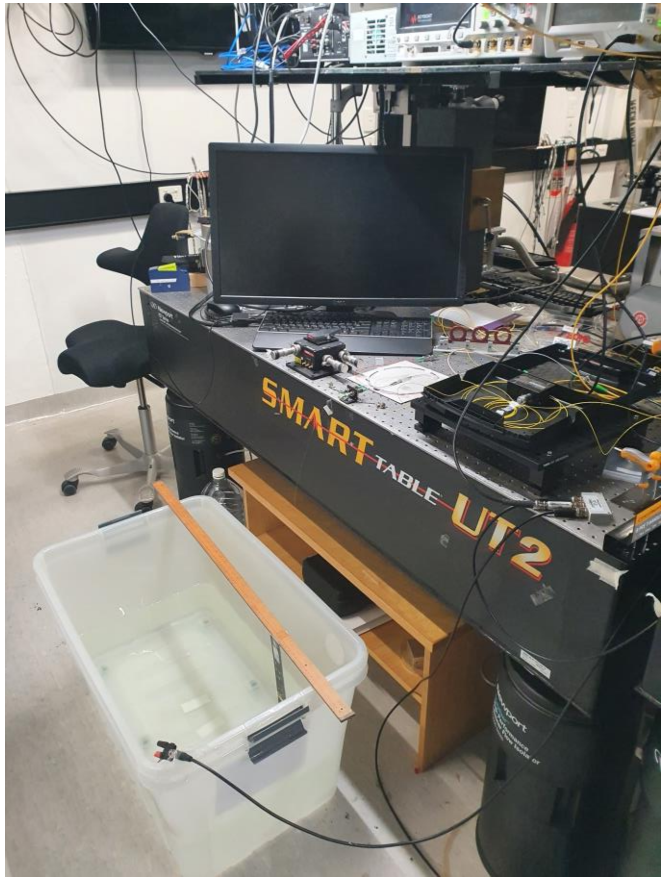
- We develop and demonstrate **acoustic sensing using a nanometre-sized acoustic sensor based on 1D photonic crystals (PhC)**
- Light is coupled into the device waveguide, and the resonant wavelength is trapped in the PhC defect "cavity"
- Acoustic pressure changes the refractive index of the surrounding material, changing the resonant wavelength

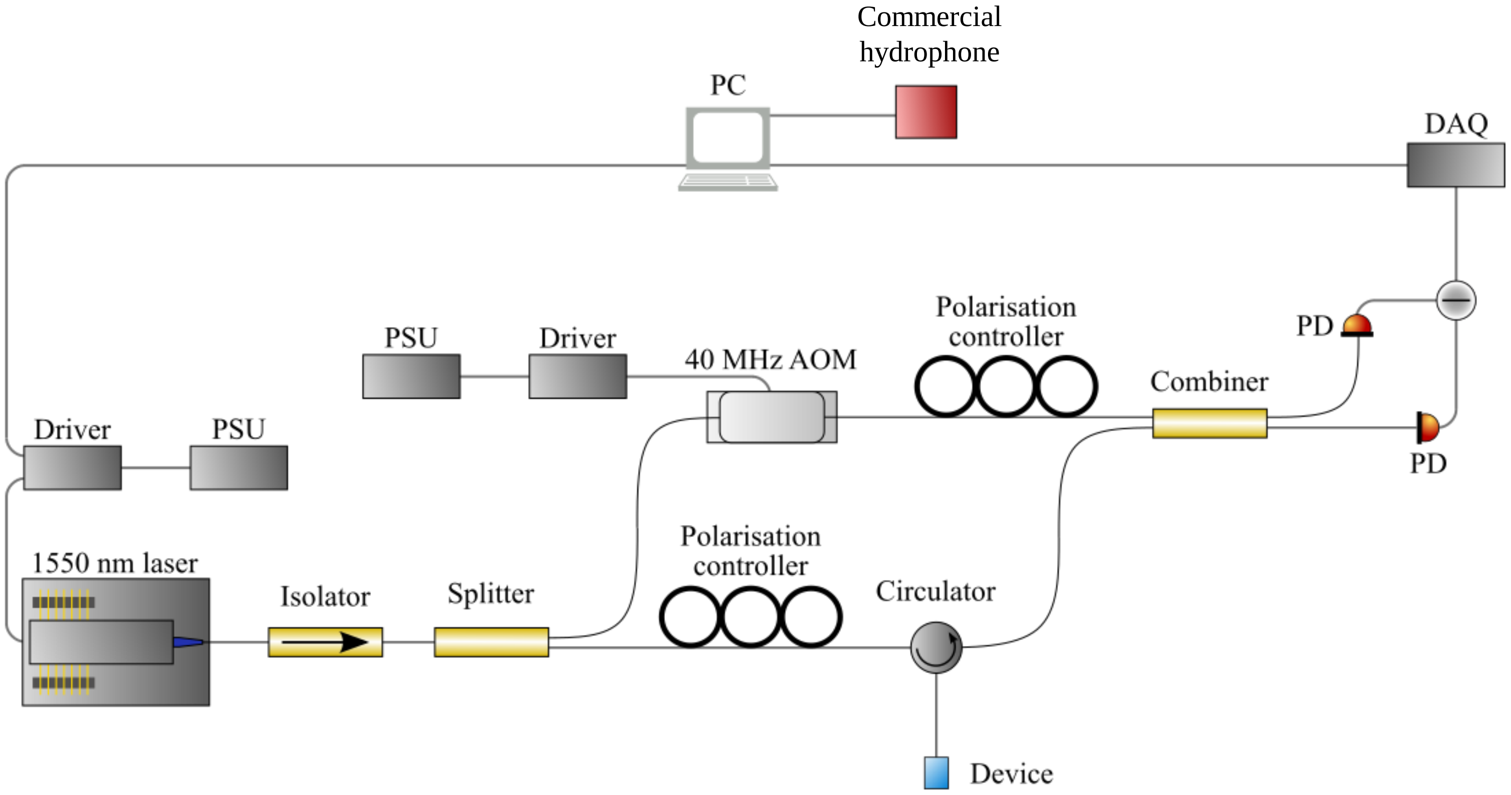


Acoustic Characterisation

The University of Queensland
Australia
EQUS

Acoustic Characterisation

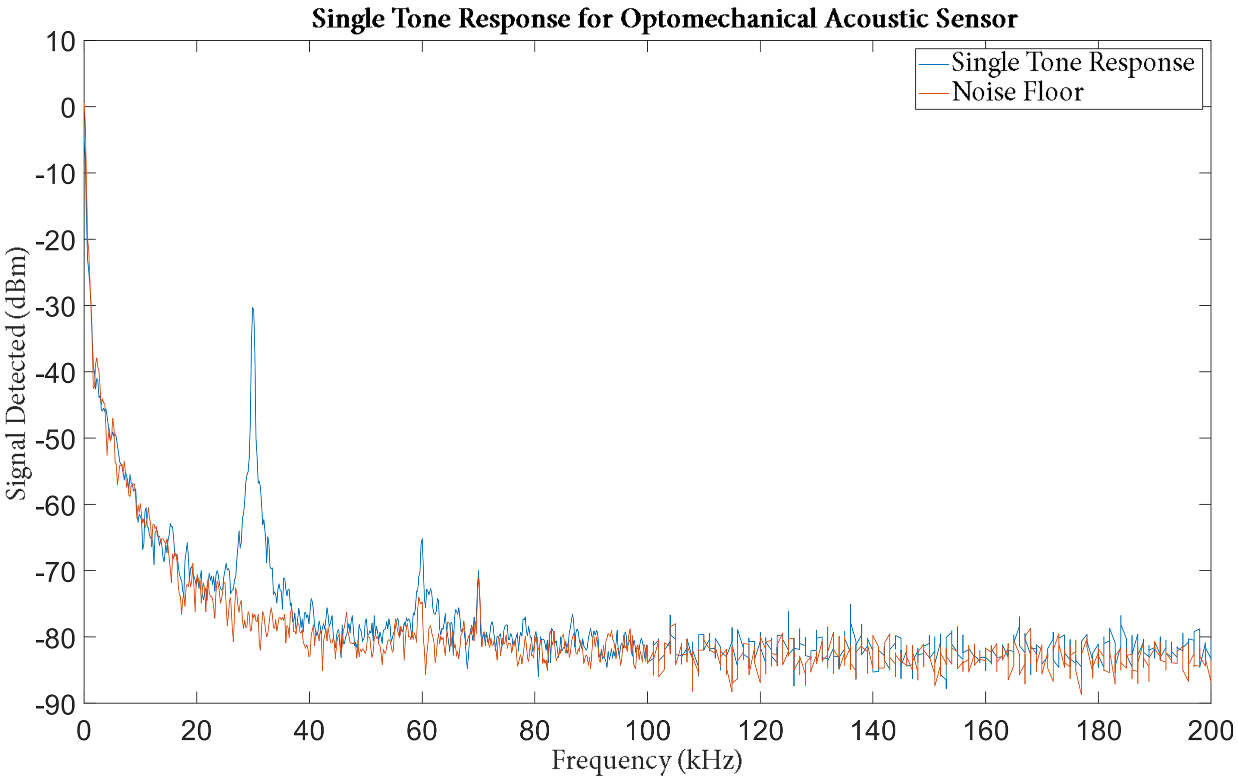




Devices are submerged in bucket of water and response to signal is monitored with heterodyne system

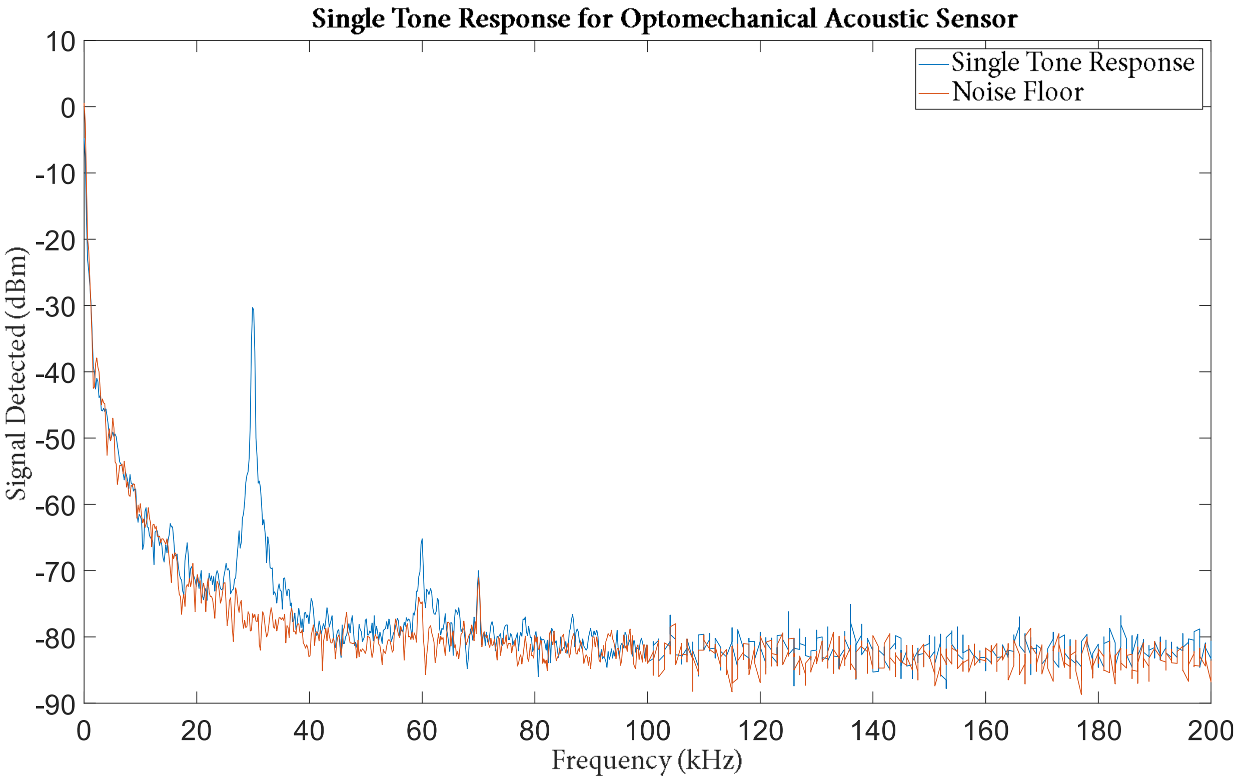
Device Characterisation Results

Device Characterisation Results

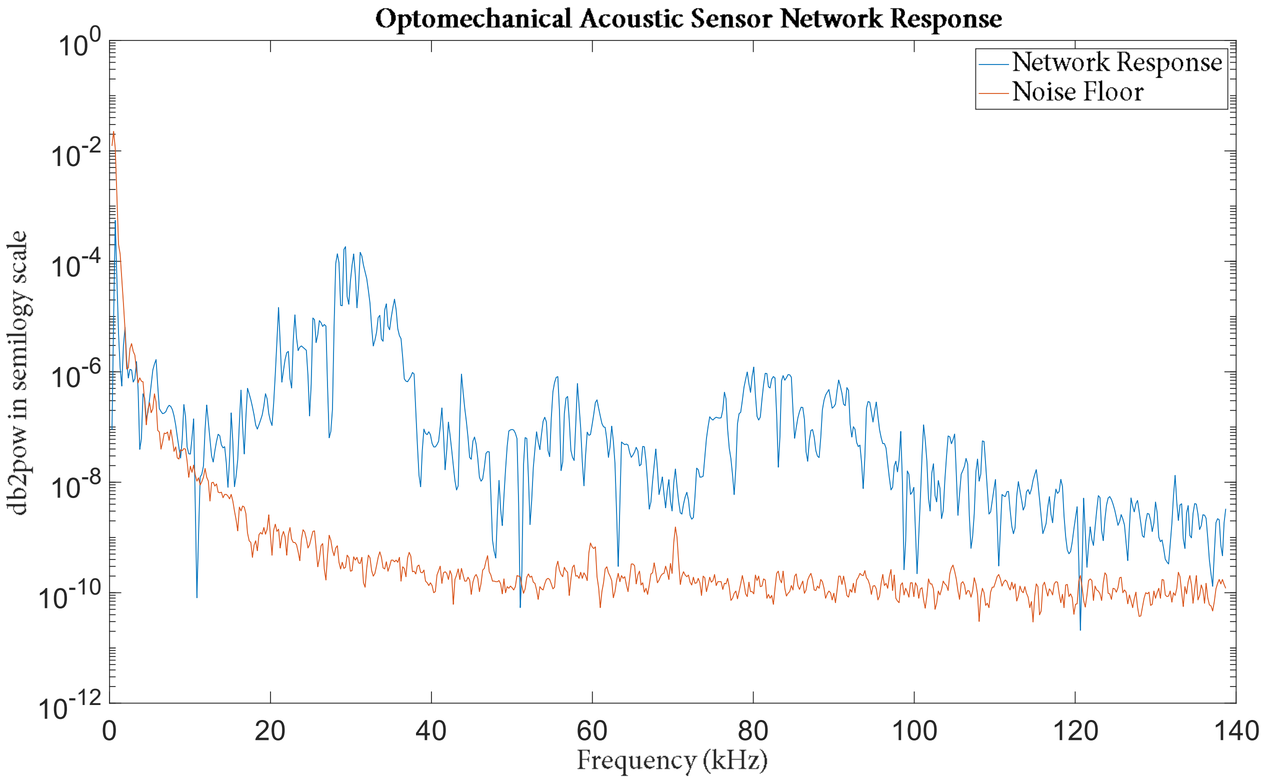


Single tone response at 32 kHz

Device Characterisation Results



Single tone response at 32 kHz



Network response with noise floor measured with spectrum analyser

Device Characterisation Results

Device Characterisation Results

Sensitivity calculated using formula:

$\tau = \Delta f^{-1}$, where Δf is the resolution bandwidth

$$P_{\text{min}}(\omega) = \sqrt{\frac{\tau}{SNR}} \times P_{\text{applied}}(\omega)$$

Signal-to-noise ratio

Applied pressure, modelled with commercial hydrophone

Device Characterisation Results

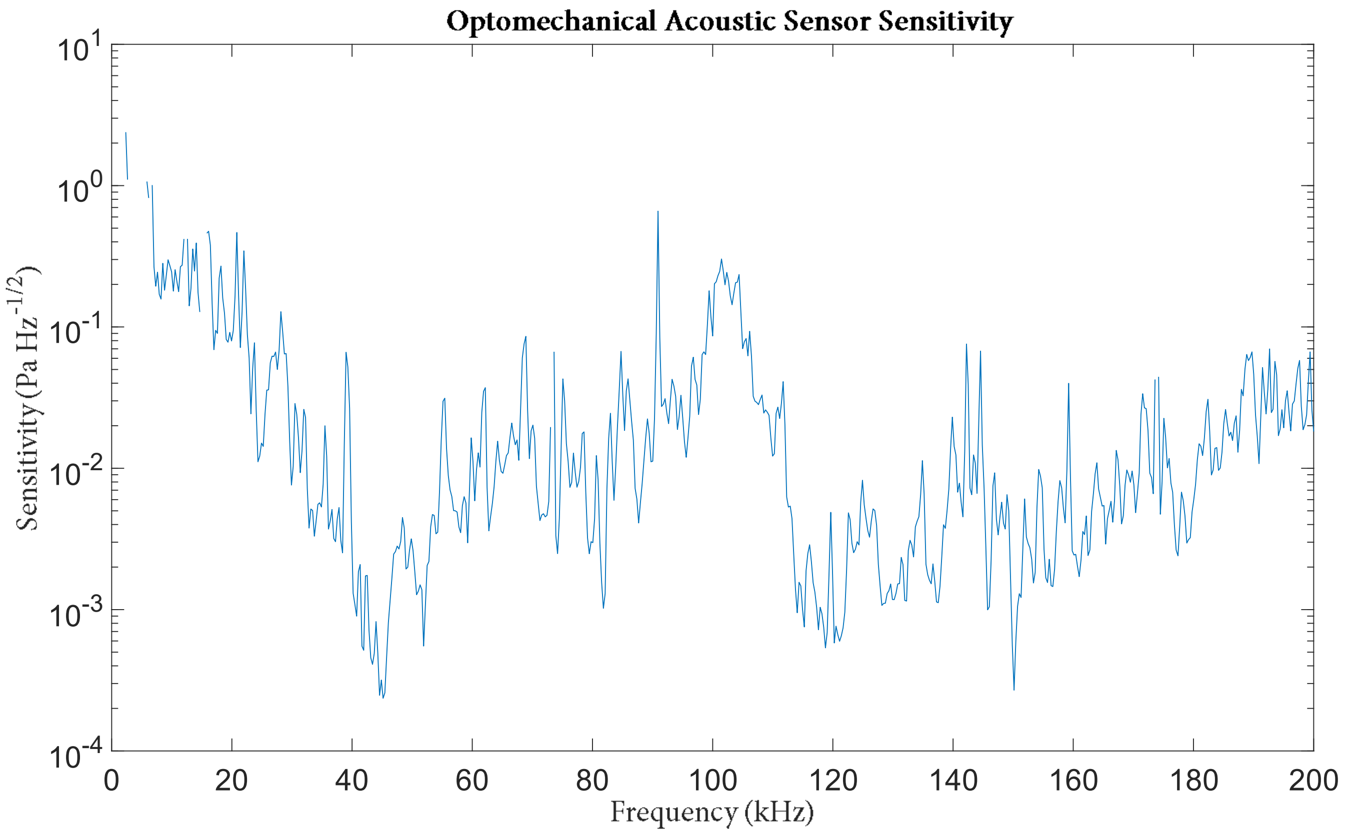
Sensitivity calculated using formula:

$\tau = \Delta f^{-1}$, where Δf is the resolution bandwidth

$$P_{\text{min}}(\omega) = \sqrt{\frac{\tau}{SNR}} \times P_{\text{applied}}(\omega)$$

Signal-to-noise ratio

Applied pressure, modelled with commercial hydrophone



Device Characterisation Results

Sensitivity calculated using formula:

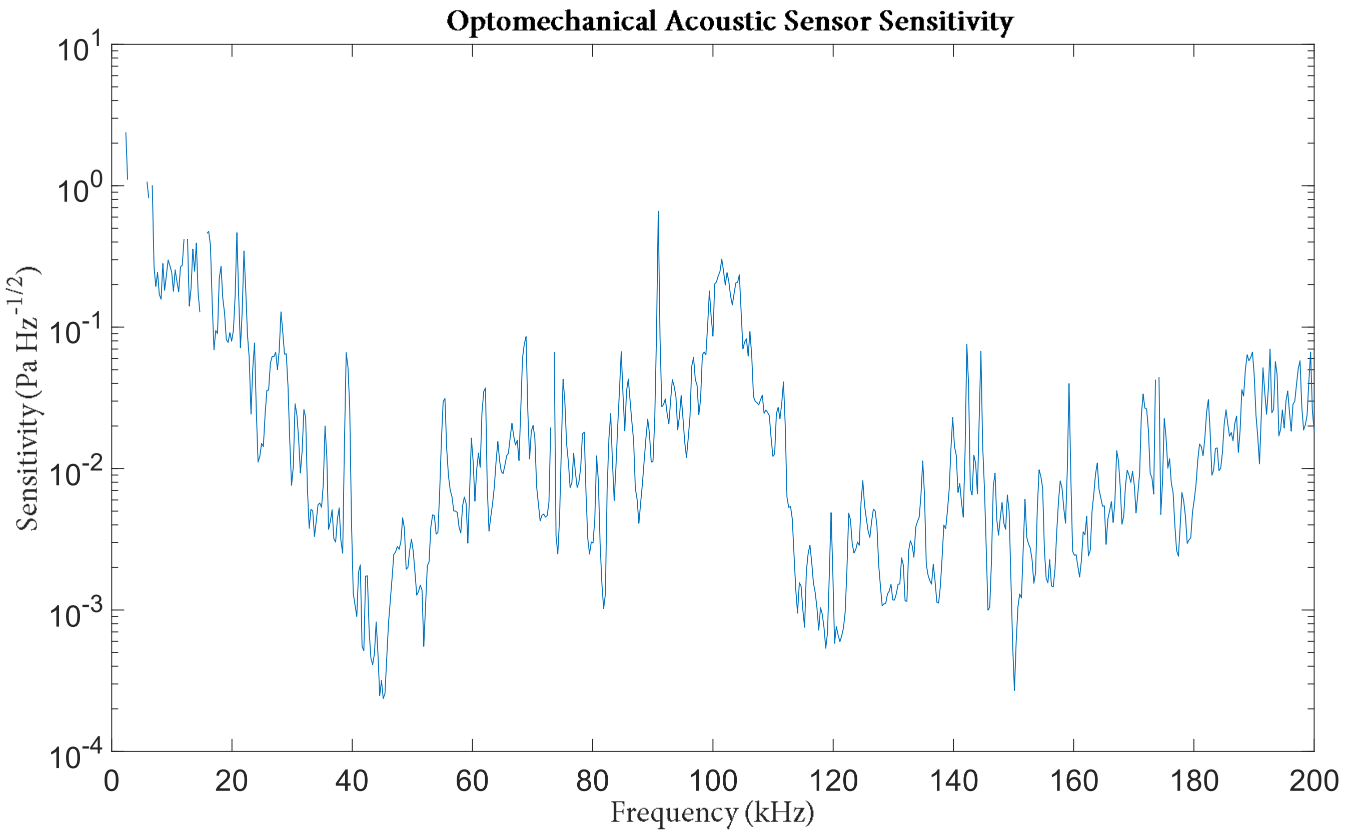
$\tau = \Delta f^{-1}$, where Δf is the resolution bandwidth

$$P_{\min}(\omega) = \sqrt{\frac{\tau}{SNR}} \times P_{\text{applied}}(\omega)$$

Signal-to-noise ratio

Applied pressure, modelled with commercial hydrophone

Optomechanical device demonstrates **comparable sensitivity to commercial hydrophone** (~mPa/$\sqrt{\text{Hz}}$) but **10 orders of magnitude smaller**



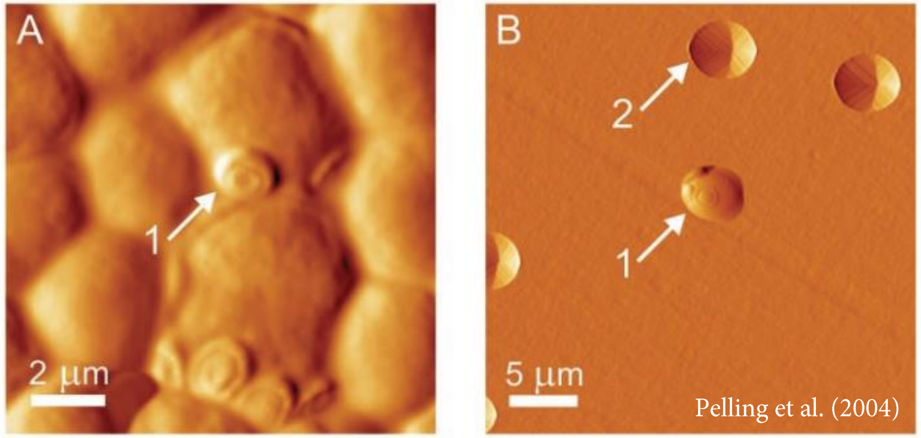
Future Outlooks

Future Outlooks

Biological sensing applications

- Use fibre-based 1D PhC sensors to try and sense acoustic vibrations from cells

- Currently building set-up for biological sensing

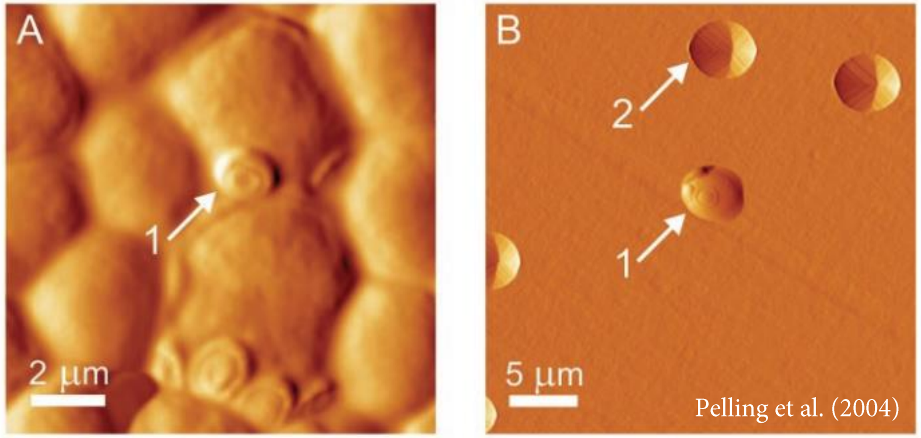


Pelling et al. (2004)

Future Outlooks

Biological sensing applications

- Use fibre-based 1D PhC sensors to try and sense acoustic vibrations from cells
- Currently building set-up for biological sensing



Pelling et al. (2004)

Defence/engineering applications

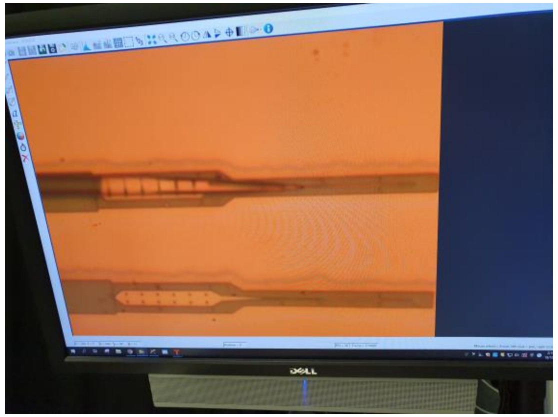
- Currently organising for field deployment in UQ swimming pool
- Deploy and characterize fibre-based sensors


University of Queensland (2022)

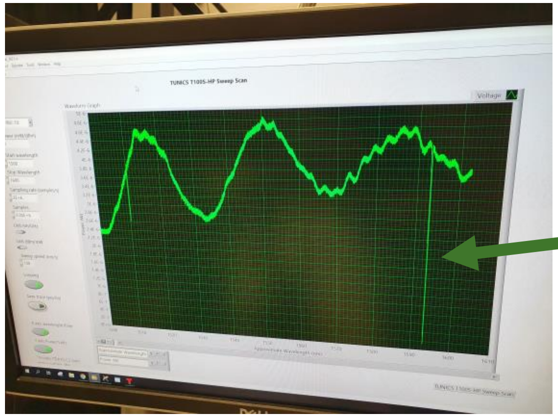
Device Preparation

Once devices are fabricated, there are two key next steps:

Device testing



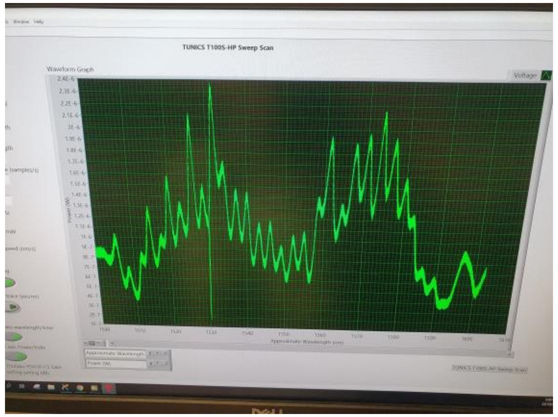
Laser light is coupled to the device



All wavelengths except the resonant wavelength are reflected back

Dips in reflected spectrum are resonances. High quality-factor and dip depth are desirable

Device preparation



Device is lifted off the chip with optical fibre, and then coated in polymer coatings for protection

Testing, Preparation and Characterisation Challenges

THE UNIVERSITY OF QUEENSLAND AUSTRALIA

EQUS

	Challenge		Solution
1	Reduced light coupling	→	Adjust tapered fibre position relative to cavity
2	Acoustic reflections in container	→	Move from small glass to large plastic container
3	Devices breaking off tapered fibre	→	New device preparation procedure
4	Optical noise in signal response	→	New heterodyne set-up