Active Phononic Metamaterials

Geoff Nash, Natural Sciences

Contents

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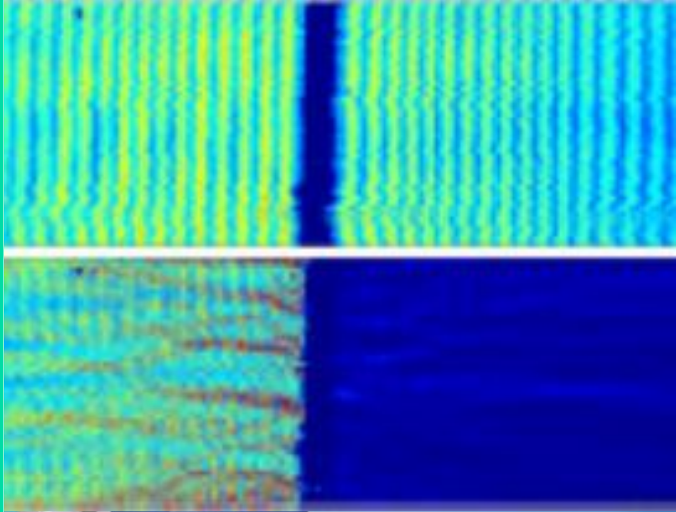
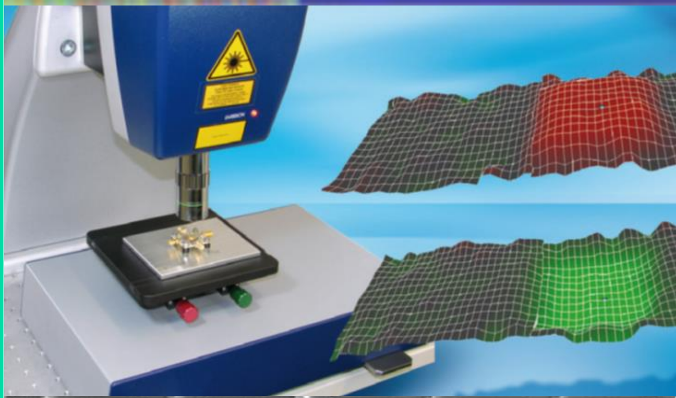
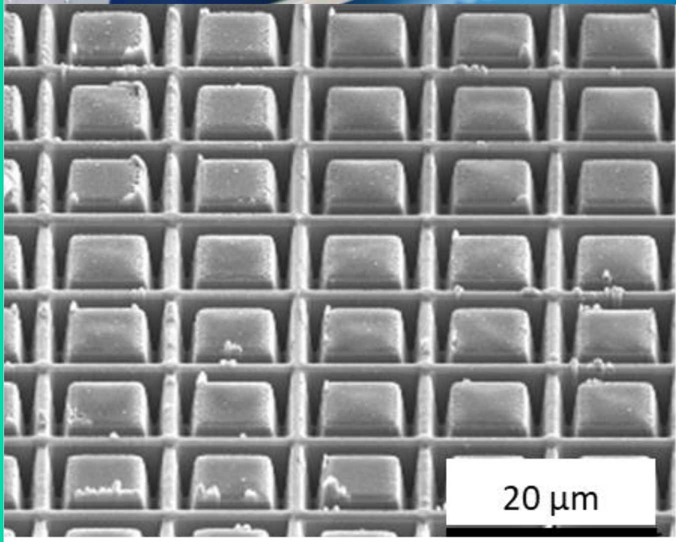
Introduction

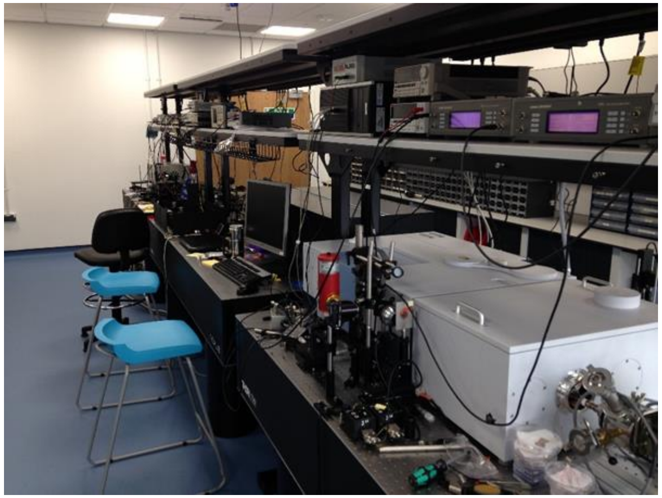






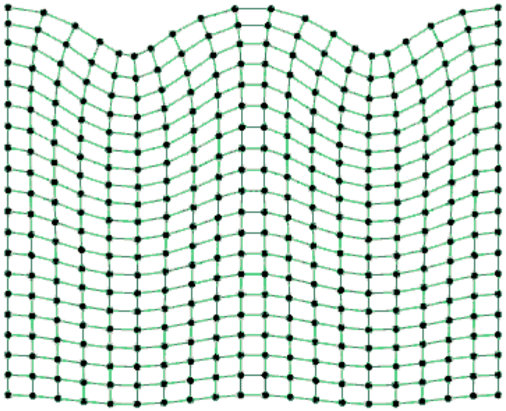
My Research

- Broadly "nanoscience"
- Modelling and theory
- Materials/device fabrication (even a little chemistry)
- Characterisation and spectroscopy
  - full suite of infrared (2-50μm) characterisation including spectrometers, lasers, infrared camera
  - GHz Laser Doppler Vibrometry
- Collaborative research
- Analytical services



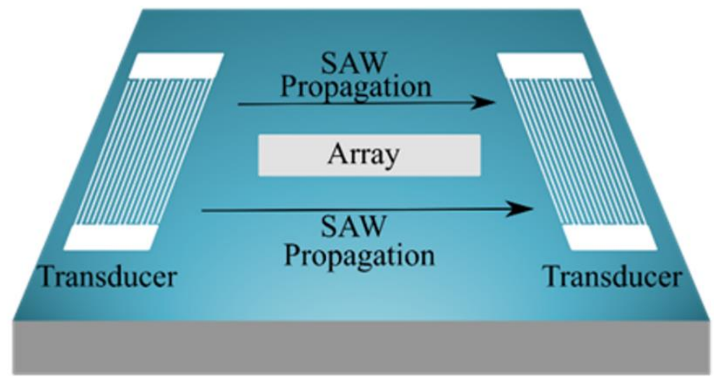
Surface Acoustic Waves

- Propagate along the surface of a solid like a tiny earthquake, or like waves on the surface of the ocean
  - First discussed by Lord Rayleigh in 1855
- Displacements less than 1nm
- Velocity approximately 4000m/s, wavelength ~10μm
- SAW devices used in mobile phones, radar systems, microfluidics, sensors etc

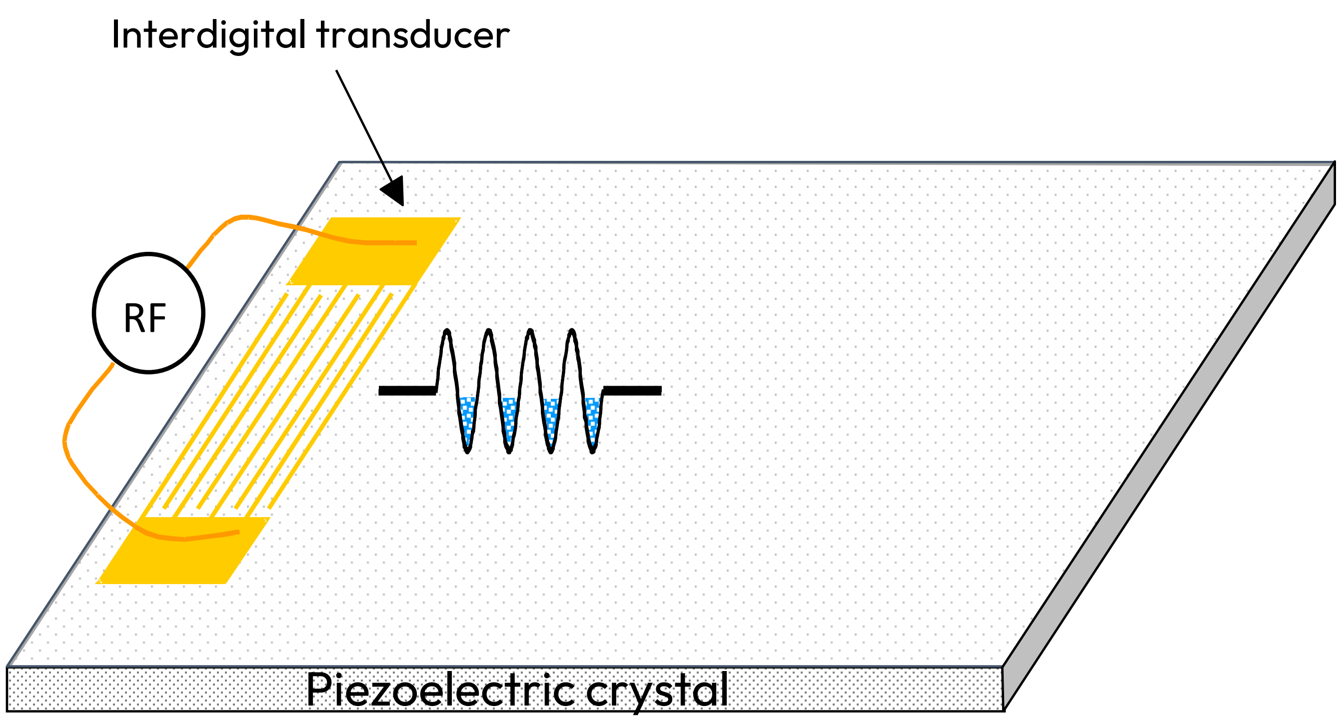


Surface Acoustic Waves Devices

- Interdigital transducer used to excite, and detect, SAWs propagating on a piezoelectric substrate
- Common substrates are quartz and lithium niobate



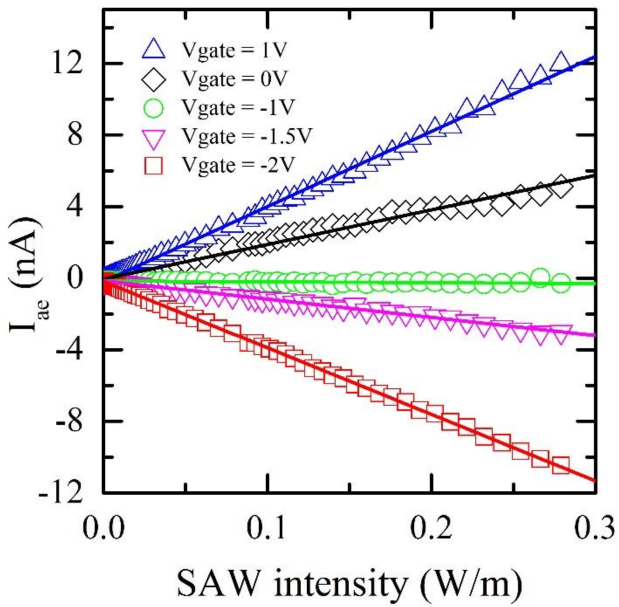
Surface Acoustic Waves Devices



Can pick up and move water, cells etc

Gate Switchable Acoustoelectric Current

- Can control whether electrons or holes are being transported



Surfing electrons!

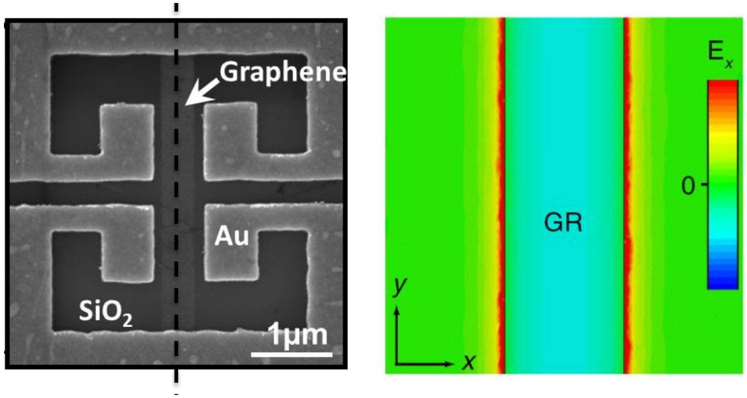
L. Bandhu and G. R. Nash, *"Voltage Control of Surface Acoustic Waves using Graphene"*, Nano Research **9**, 685 (2016).

Metamaterials

- Artificial materials that can be designed to have properties that natural materials don't posses

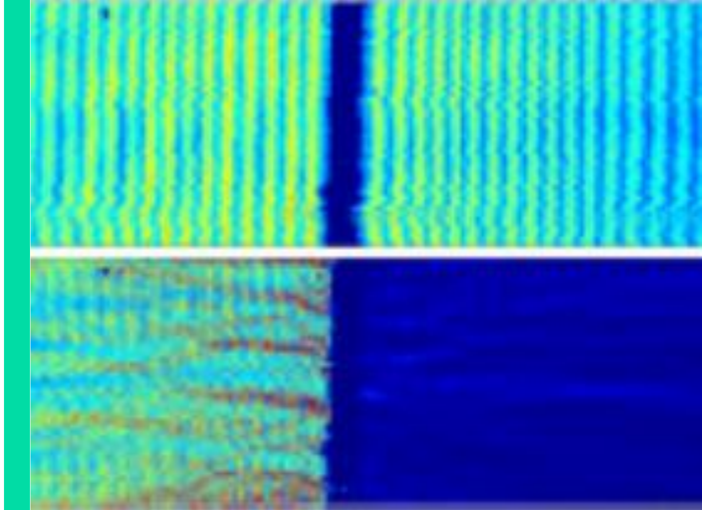
- Can be designed to control the flow of light, electromagnetic radiation, sound etc

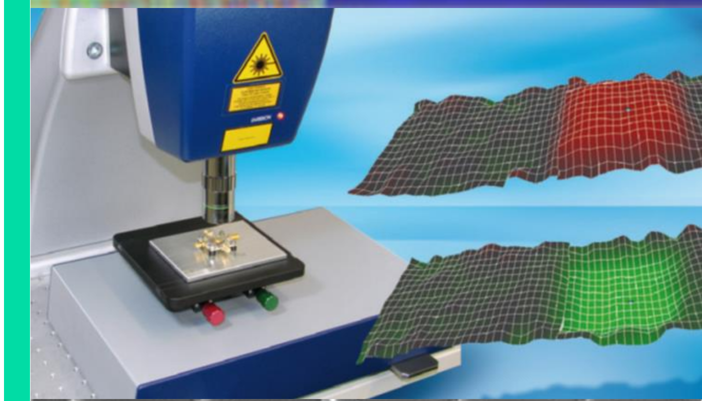
- Structure consists of "meta-atoms" that come together to form new material

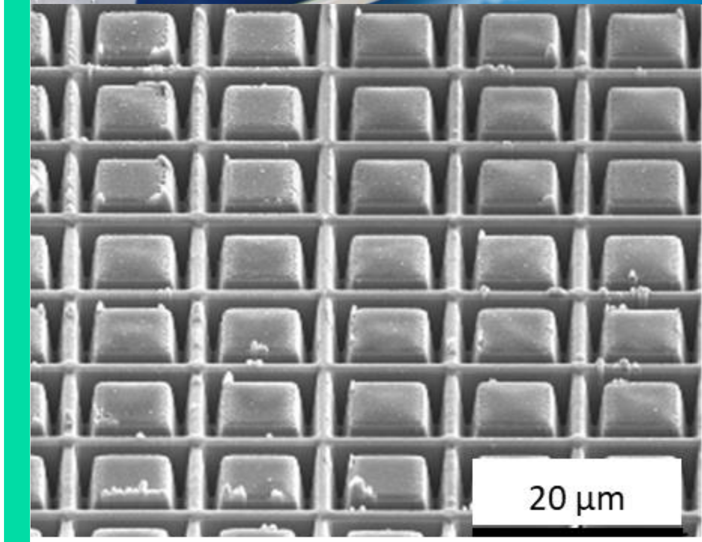


Liu *et al*, Nature Communications **6,** 8969 (2015).

Phononic Crystals

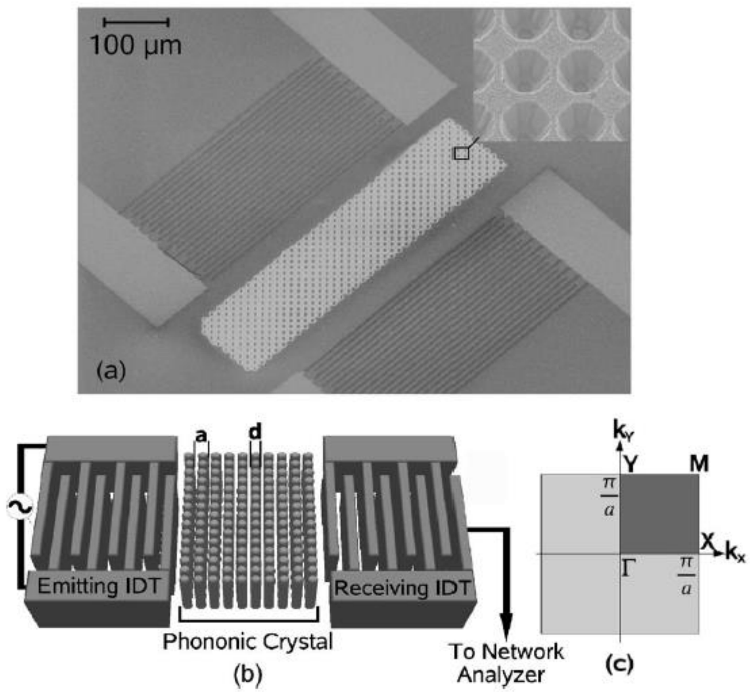






Background

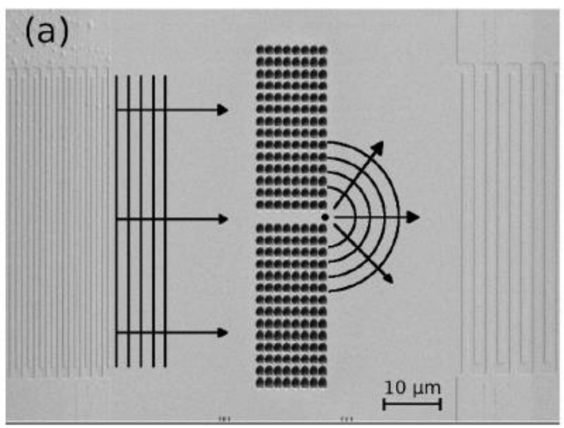
- Patterning of holes in substrate, in analogy with photonics, leads to a bandstructure/bandgap
- Propagation at particular frequencies blocked
  - inherently a filter
  - At frequencies above the bandgap get coupling of SAWs into bulk modes
    - large attenuation at frequencies other than the bandgap
  - Active filters would be really attractive for a lot of applications
  - Not a metamaterial?

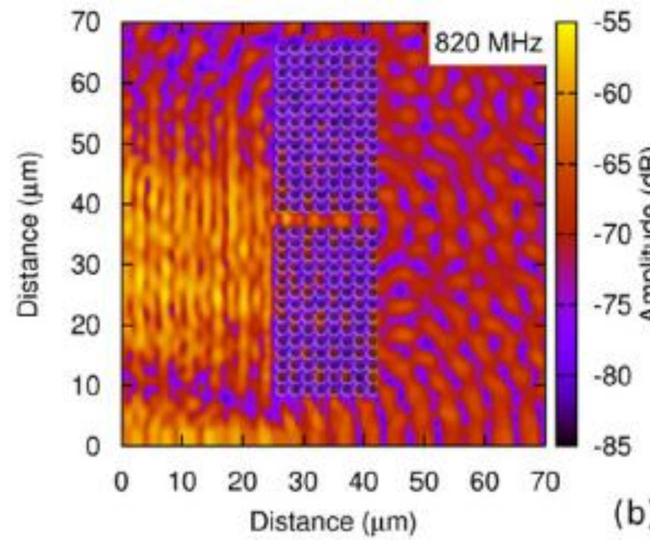


S. Benchabane, A. Khelif, J. -Y. Rauch, L. Robert and V. Laude, "*Evidence for complete surface wave band gap in a piezoelectric phononic crystal*" *Phys. Rev. E* **73**, 065601 (2006).

Waveguiding

- One use of phononic crystals is to create waveguides, cavities etc
- Potential applications in signal processing, sensing
- Dynamic control would allow SAW propagation to be steered





S. Benchabane, O. Gaiffe, R. Salut, G. Ulliac, V. Laude and K. Kokkonen, "*Guidance of surface waves in a micron-scale phononic crystal line-defect waveguide*" *Appl. Phys. Lett.* **106**, 081903 (2015)

Origin of Bandstructure

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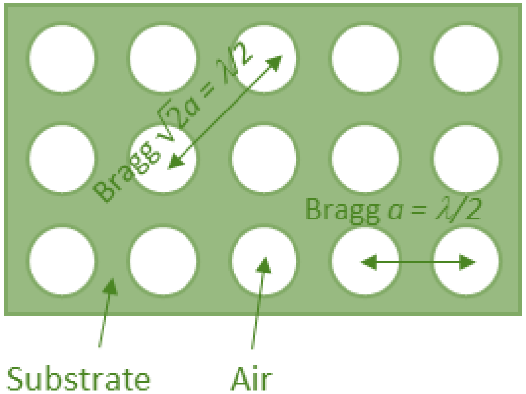
- Bandgaps are defined by the pitch and filling fraction of periodic arrays principally through Bragg scattering
  - may also have Mie scattering
- Can tailor the properties of the array by **changing** the geometry
- To actively tune the characteristics could change the properties of the elastic material in the holes
  - reflection coefficient at the interface between two media is dependent on the difference in their acoustic impedances
  - acoustic impedance is given by $\sqrt{E\rho}$, where E = modulus, ρ = density



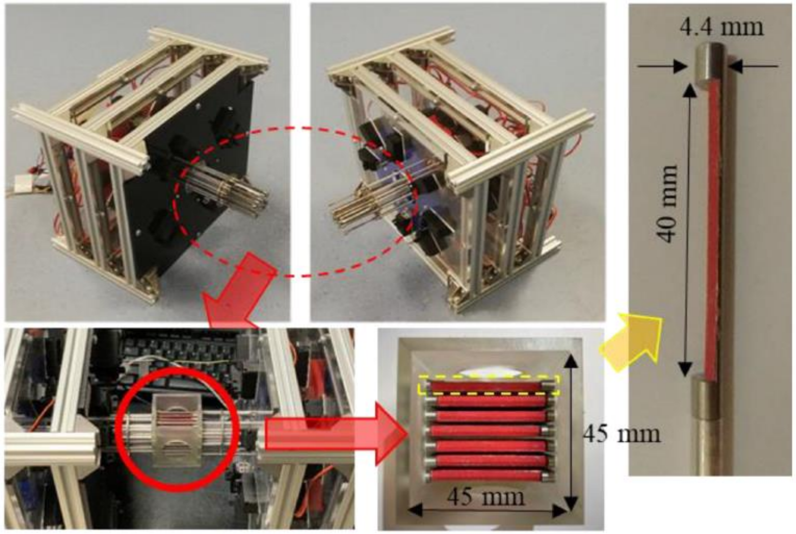
$$f(\text{Bragg})_{\Gamma X} = \frac{V_{\text{avg}}}{2a},$$

$$f(\text{Bragg})_{\Gamma M} = \frac{V_{\text{avg}}}{(2a)\sqrt{2}},$$

R. H. Olson and I El-Kady, "*Microfabricated phononic crystal devices and applications*", Meas. Sci. Technol. **20**, 012002 (2019)

Approaches to Tunability

- At macroscopic scales many different approaches have been taken to achieve tunabilty
  - dynamically changing the geometry, or by the use of photosensitive polymers
- Not trivial to translate these approaches to the microscopic scale for SAW devices
  - can't really dynamically vary the geometry
  - processing of SAW substrates challenging
- Could try and fill the holes with a tuneable elastic material, but not easy
- Times are also challenging – at 4000 m/s, propagation time around 1μs



H. Heo , A. Krokhin , A. Neogi, Z. Cui , Z. Yuan, Y. Hua, J. Ju, and E. Walker, " " *Phys. Rev. Appl.* **19**, 0854008 (2023)

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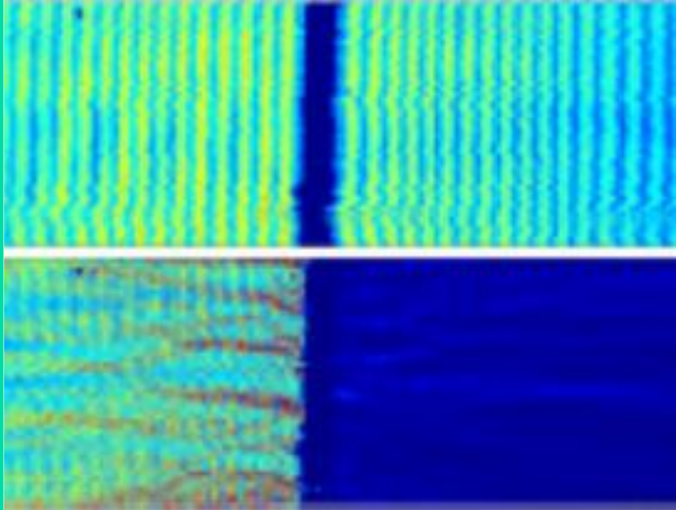
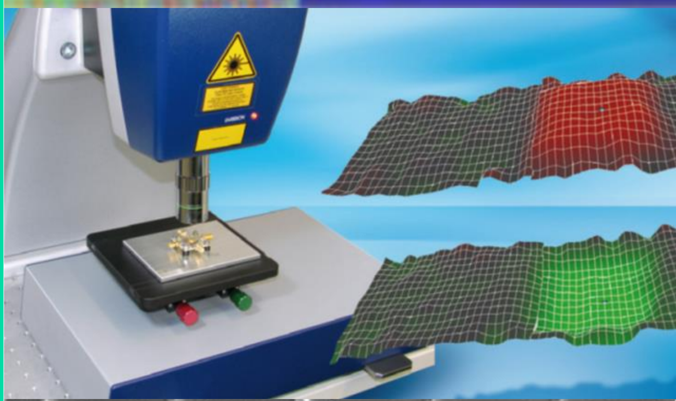
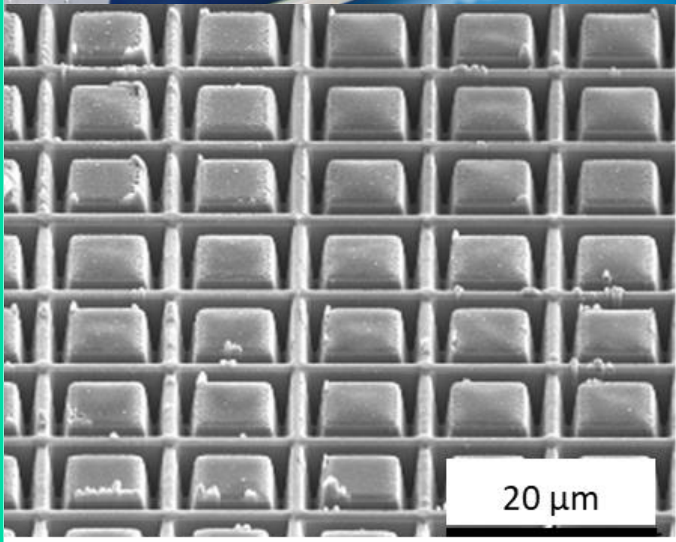
Annular Hole Resonators

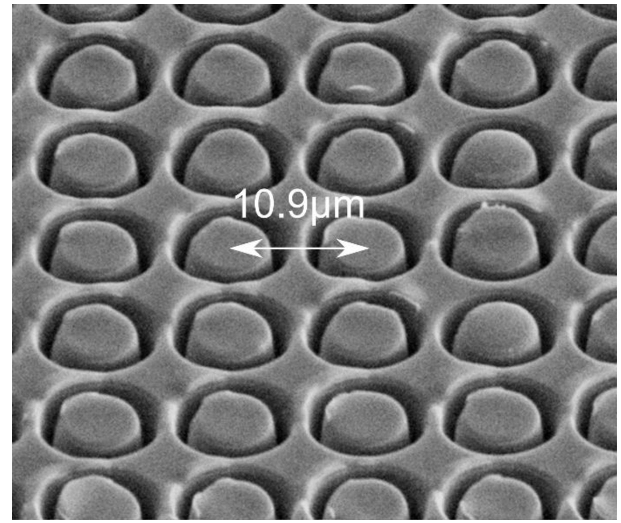


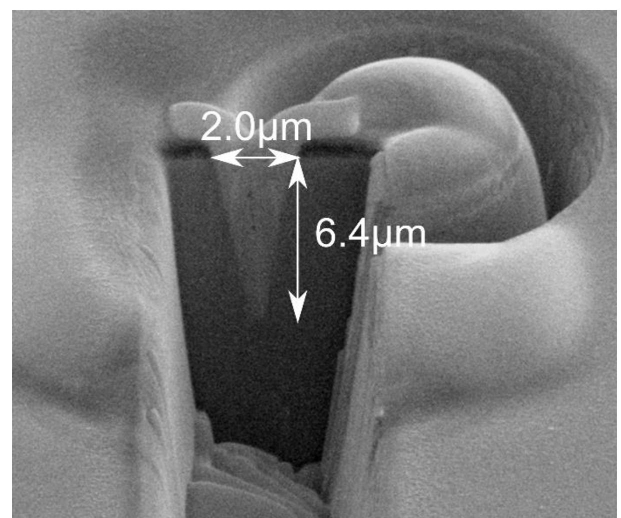




Rationale

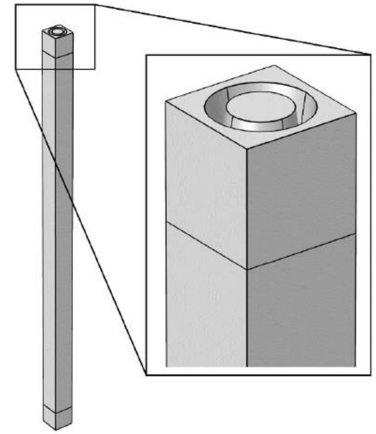
- Undergraduate project
  - aim was to study phononic crystals using commercially available lithium niobate SAW delay lines
- Designed phononic crystals using COMSOL, then using a focussed ion beam system to pattern holes
- However, lithium niobate is an extremely hard material
  - making large areas in the time available not feasible

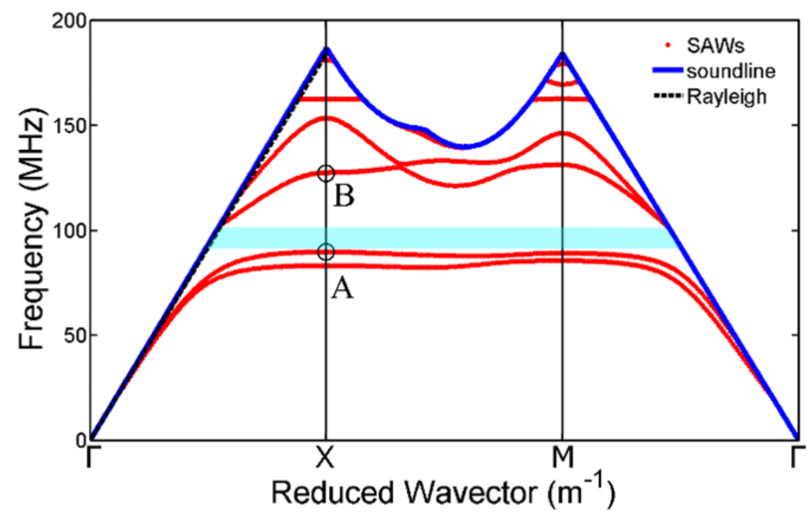




Bandstructure

- Bandstructure calculated using eigenfrequency model in COMSOL
- The blue and red lines represent the soundline and SAW bands respectively
- A complete bandgap shaded in teal has been created at a low frequency
  - observable propagating SAW modes for frequency ranges both above and below the gap

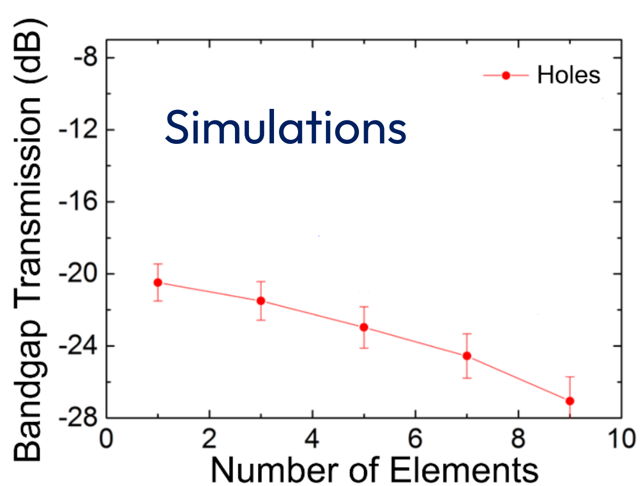


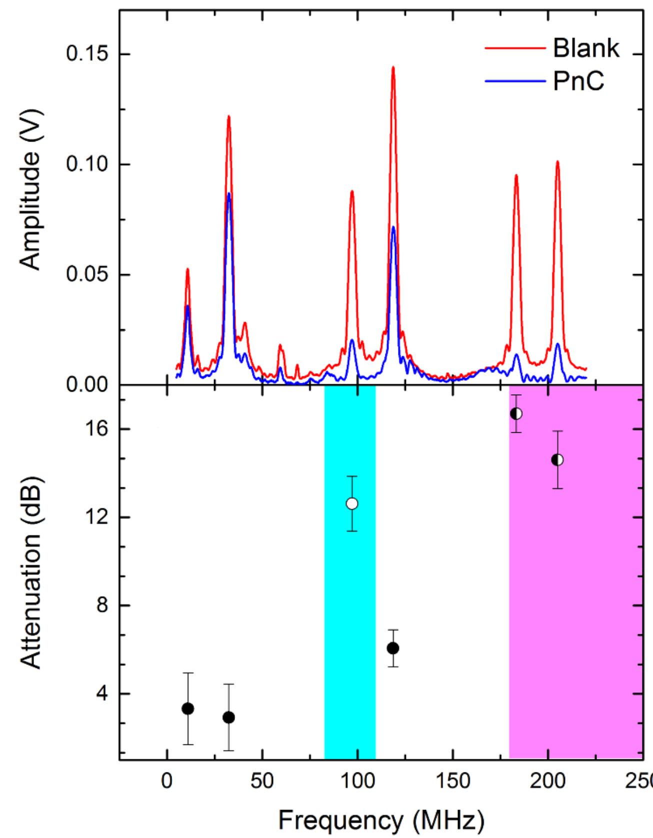


B. J. Ash, S. R. Worsfold, P. Vukusic, G. R. Nash, *"A highly attenuating and frequency tailorable annular hole phononic crystal for surface acoustic waves"*, Nature Communications **8**, 174 (2017).

Bandgap Attenuation

- Bandgap attenuation calculated using a transmission model in COMSOL
- Get extremely high bandgap attenuation achieved with a small number of elements
- Attenuation experimentally determined using electrical measurement and Laser Doppler vibrometry

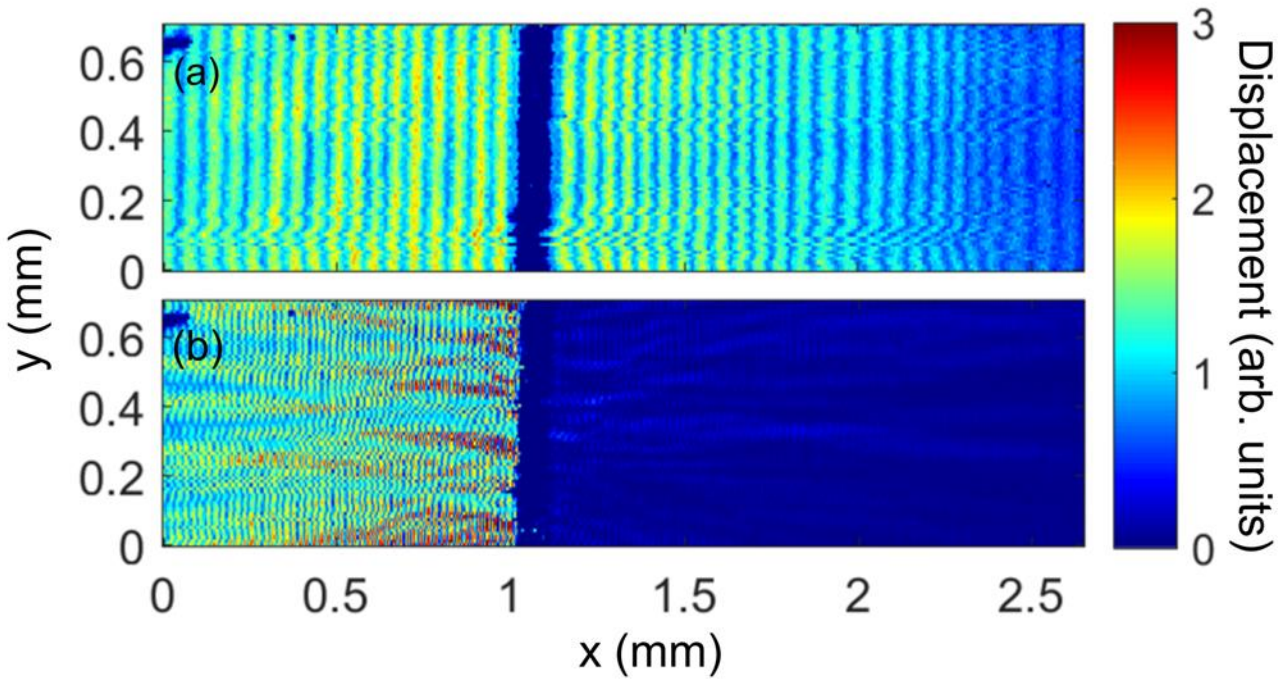




B. J. Ash, S. R. Worsfold, P. Vukusic, G. R. Nash, *"A highly attenuating and frequency tailorable annular hole phononic crystal for surface acoustic waves"*, Nature Communications **8**, 174 (2017).

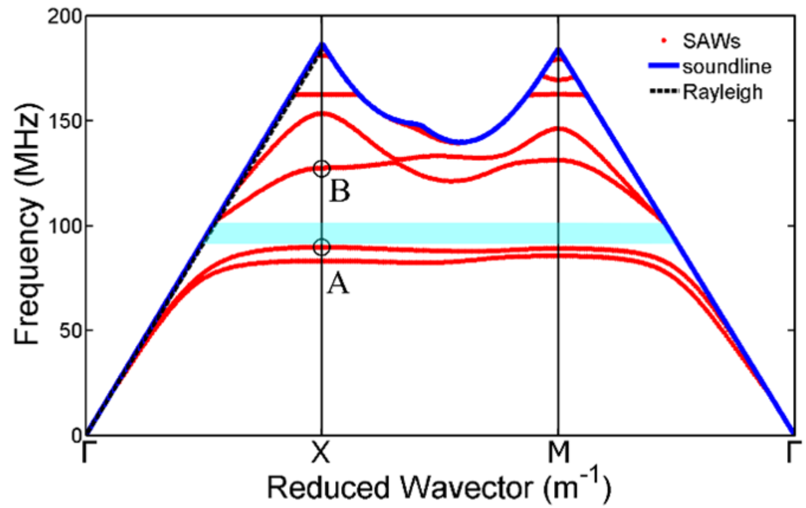
Laser Doppler vibrometry measurements

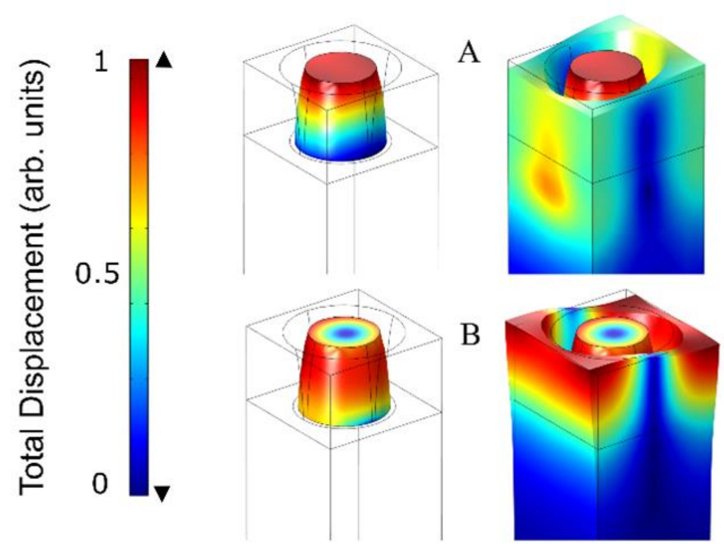
- SAWs exited continuously to the left of the image
- Colour scale represents a *time-averaged amplitude* of the SAWs. The dark strip = patterned annular hole array
- Measured attenuation at in the bandgap (97 MHz) was 24.4 dB, is in excellent agreement with the value of 24.5 dB obtained from the simulations



Displacements

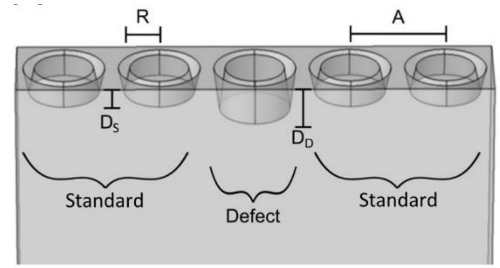
- Why is attenuation at the bandgap so high?
- Started to look at the displacements in COMSOL
- Excitation of annual holes/pillars very different at frequencies within/outside the bandgap
- Characteristics of the annular hole array now at least partly determined by the *properties of the elements* themselves

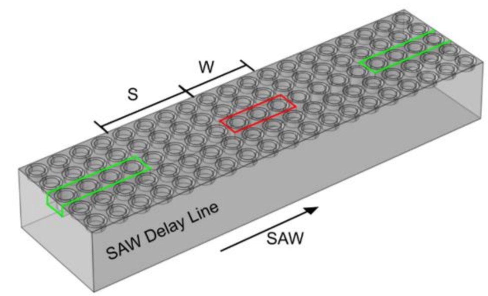


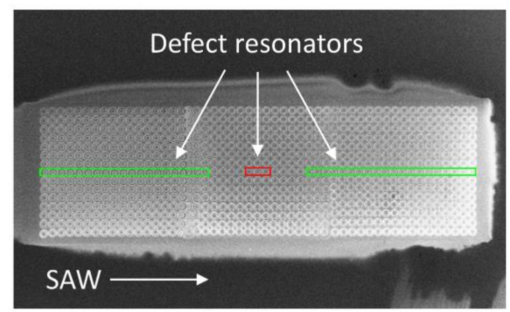


Subwavelength Confinement

- Ability to confine a propagating SAW in a subwavelength region → increase the sensitivity and functionality of SAW sensors
- Our approach was to use "defect" resonators to define coupling waveguides and a "cavity"
- Subwavelength confinement could allow entities that are much smaller than the SAW wavelength to be probed
- **Small changes to the environment of a resonating element** are likely to have a significant effect on the characteristics of the SAW propagating beyond the confining region



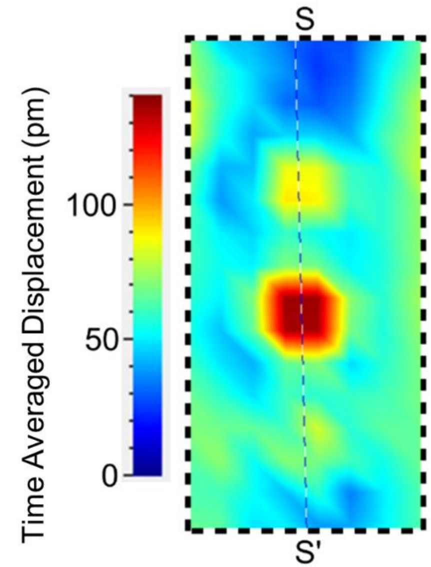


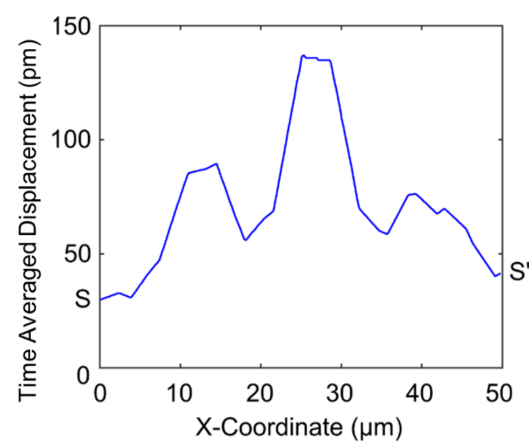


B. J. Ash, A. R. Rezk, L. Y. Yeo and G. R. Nash, *"Subwavelength confinement of surface acoustic waves"*, Appl. Phys. Lett. **118**, 013502 (2021).

Subwavelength Confinement

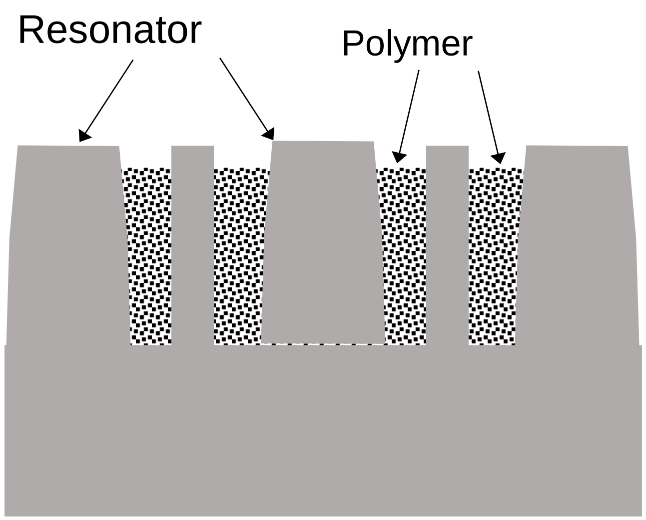
- Laser Doppler vibrometry to used verify the results obtained through simulations
- At resonant SAW frequency of 97 MHz large displacement can be seen in the three central defect
- The strong displacement observed within these resonators is consistent with the results of simulations
- Paves the way for applications needing subwavelength confinement, but also highlights some of the differences between a *phononic crystal and local resonator array*



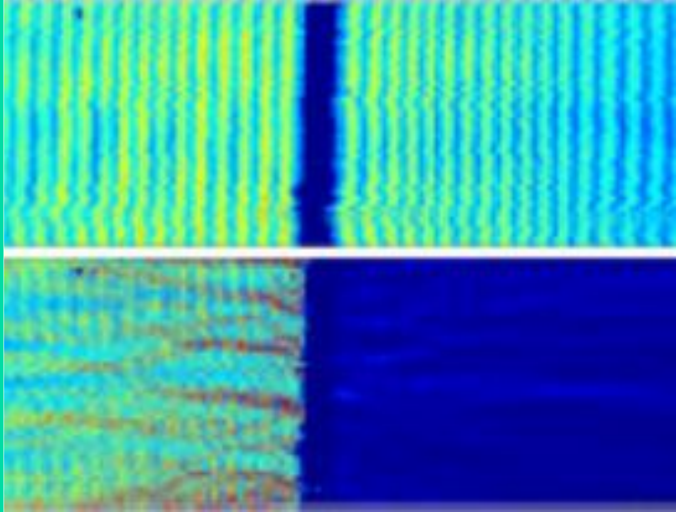


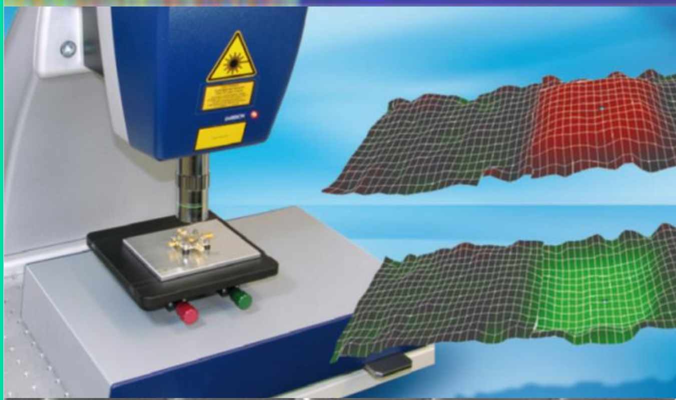
What about tunability?

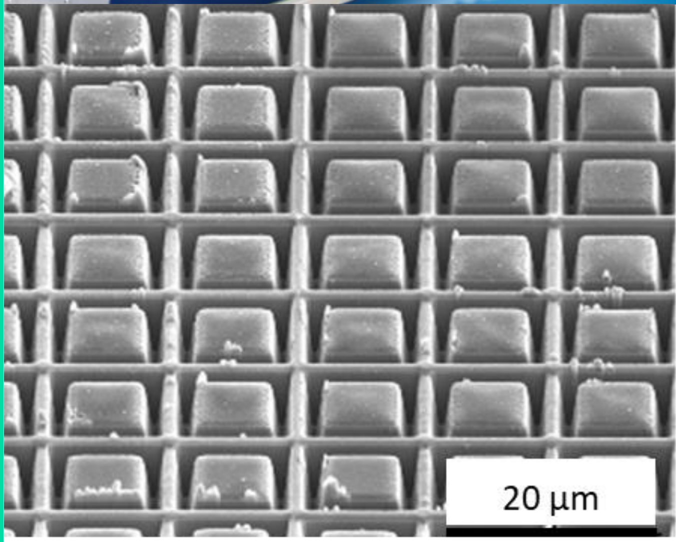
- Behaviour of individual resonators extremely sensitive to their environment
- Could try and actively control the properties of the surrounding material
- Still challenging:
  - need suitable materials to allow tunability
  - electro-, or thermo-, sensitive polymers
  - less elements, but still need to be able to fill the holes
- Does having a local resonator array (or metamaterial?) actually help?



Surface Acoustic Wave Swimming

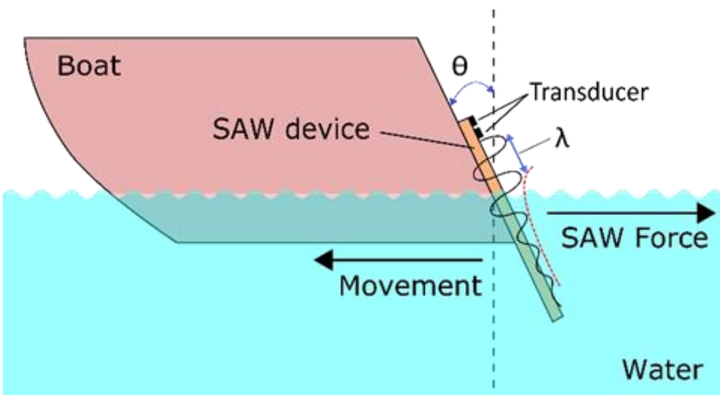






Surface Acoustic Wave Swimming

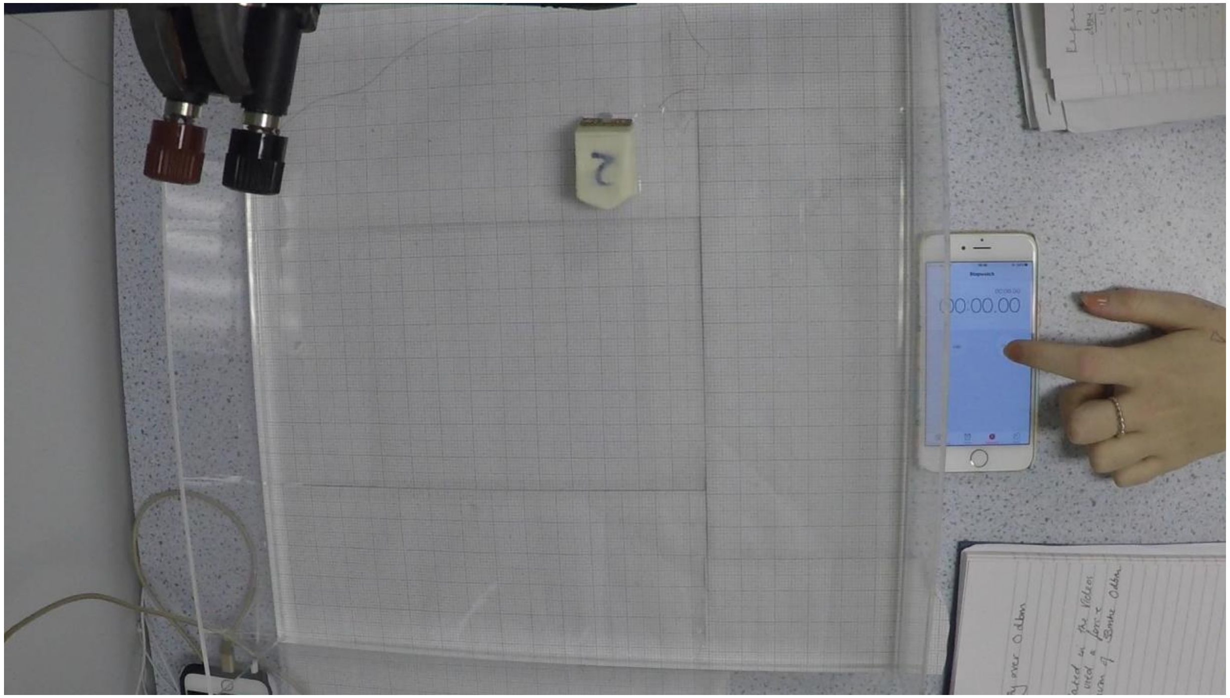
- Propulsion without moving parts
- Mimics the way some micro-organisms move
- Only observed once before*, but no theory of operation



Device has to be mounted at angle due to **refraction** of sound into the water

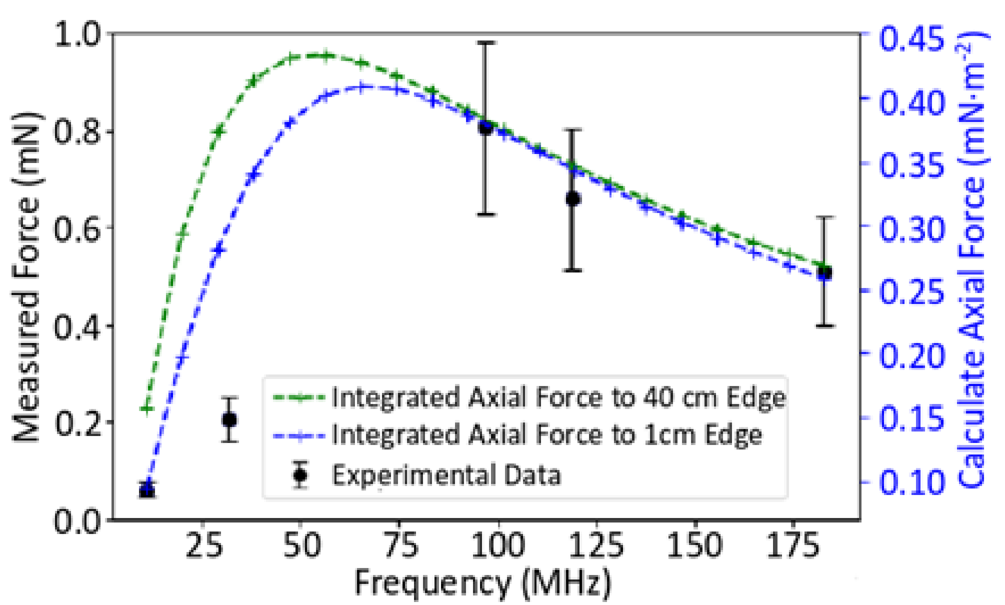
* Y. Bourquin and J. M. Cooper, "*Swimming Using Surface Acoustic Waves*", PLOS One **8**, e42686 (2013).

Another student project



Frequency/wavelength Dependence

- Theory and experiment show that the force has a maximum at a particular frequency
- Important for designing artificial swimmers, but also might be used by nature



C. Pouya, K. Hoggard, S. H. Gossage, H. R. Peter, T. Poole and G. R. Nash, *"Frequency dependence of surface acoustic wave swimming", J. R. Soc. Interface **16**, 20190113 (2019).*

Refraction

- Reducing the SAW velocity would allow devices to be create devices which more closely mimic swimming microorganisms
- Want maximum thrust when devices lie almost parallel to the surface of the fluid
- Original intention was to use a phononic crystal to modify bandstucture and velocity
- Instead started exploring an array of local resonators

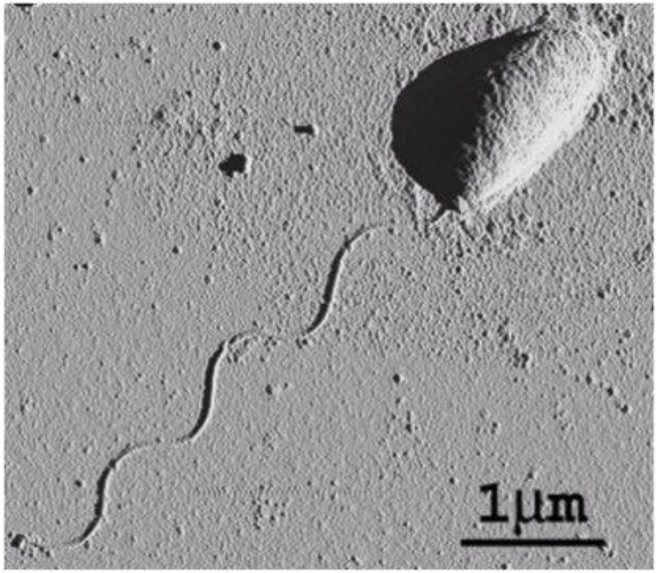
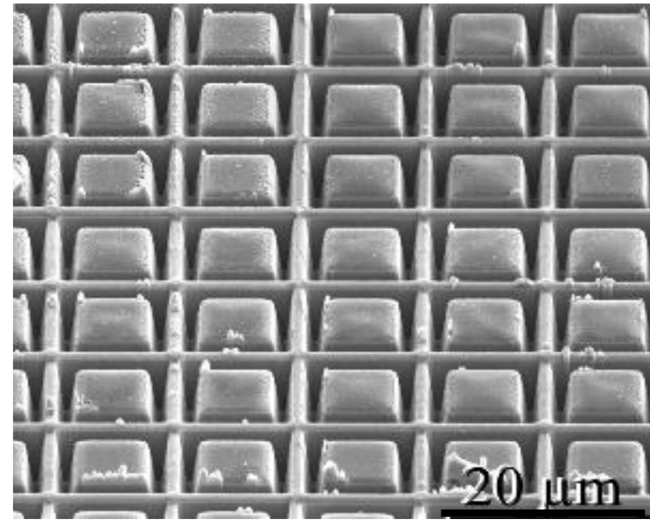


Image courtesy of Professor Jay Tang, Brown University.

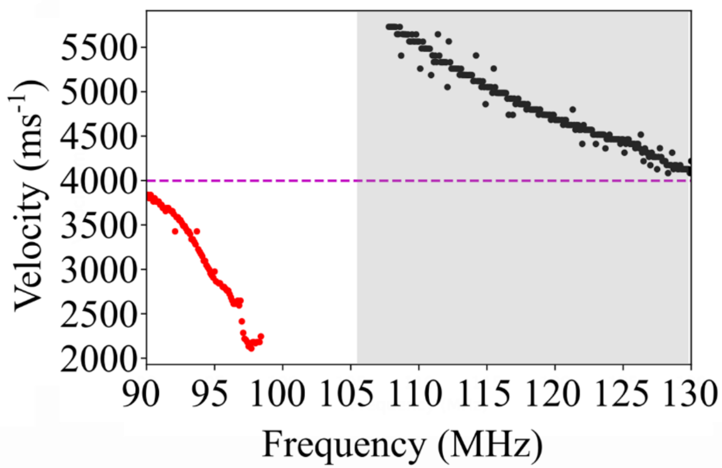
Square Annular Holes

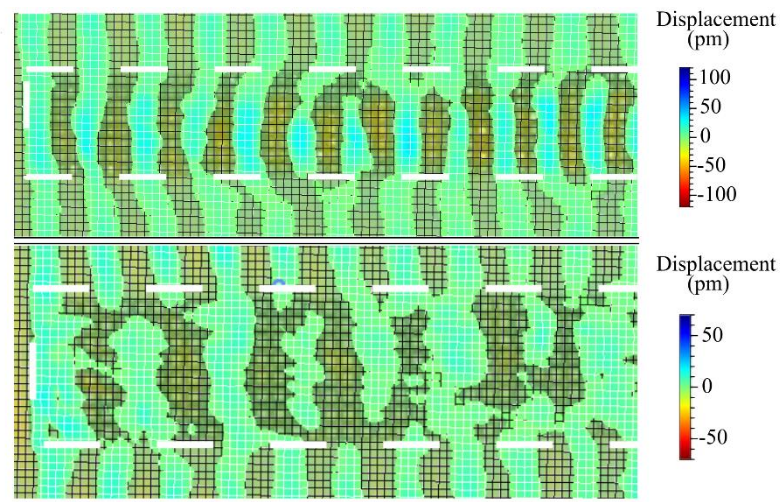
- Why use circular holes?
- Characteristics of array are partly determined by properties of resonators
- Thought of lots of different resonator geometries (e.g. asymmetric) but decided to start with a simpler alternative to circular holes
- As is often the case, nothing is ever quite as simple as you first think…



Velocity Control

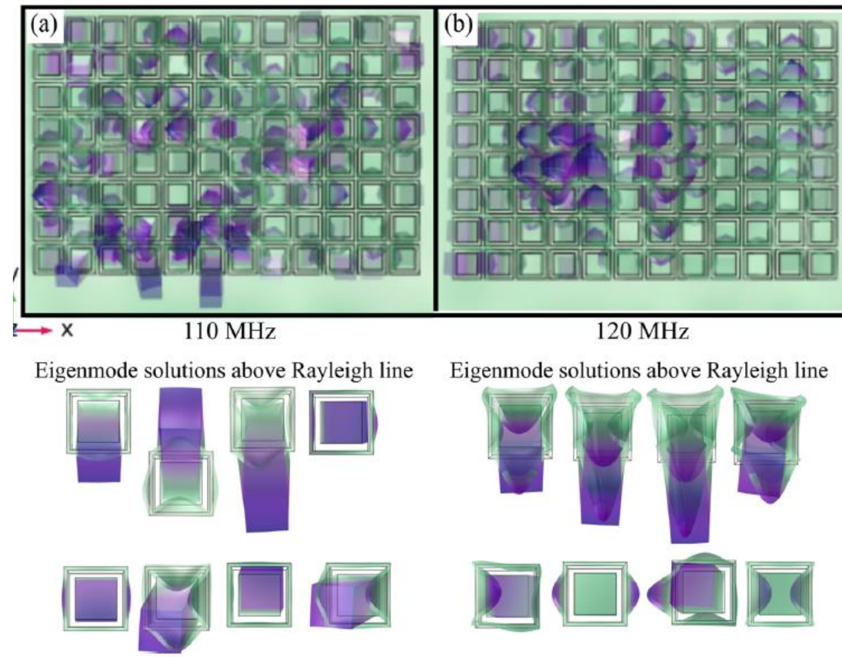
- Can control phase velocity using SAW frequency
- Simulations and experiment →
  - can obtain SAW phase velocities slower and faster than the velocity in an unpatterned substrate
  - ~85% and ~130% of the unpatterned SAW velocity, respectively





Why?

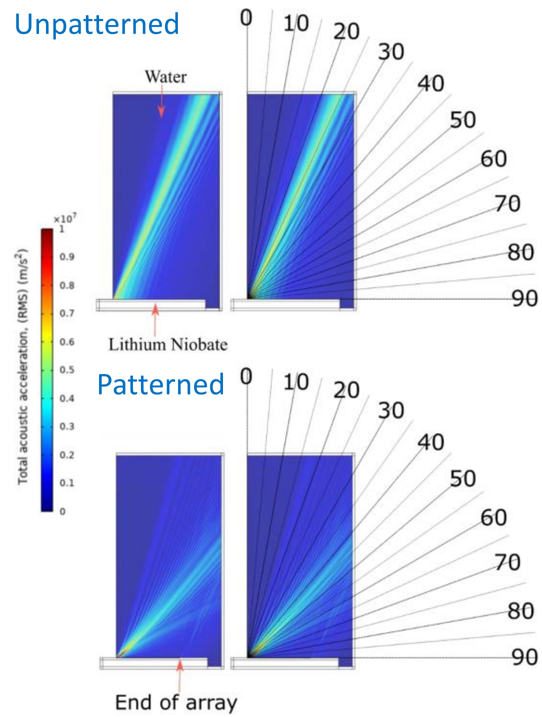
- Originates from the characteristics of the different resonator modes that SAWs can excite at different frequencies
- Slow SAWs are achieved as a result of excitation of modes with a strong Rayleigh motion
    - vertical transverse and longitudinal motion
- Fast SAWs are less Rayleigh-like
- Could be utilised in applications requiring dynamic velocity control such as wireless sensing and delay line filters
- Offers insight of how to potentially create tuneable SAW phononic devices



C. Pouya and G. R. Nash, "Sub- and Supersonic Elastic Waves in an Annular Hole Phononic Metamaterial", Commun. Mater. ***2****, 55 (2021).*

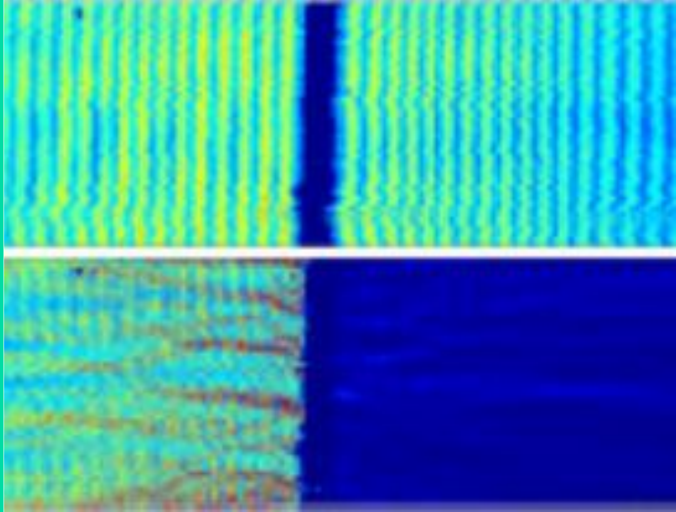
Control of Streaming Jet

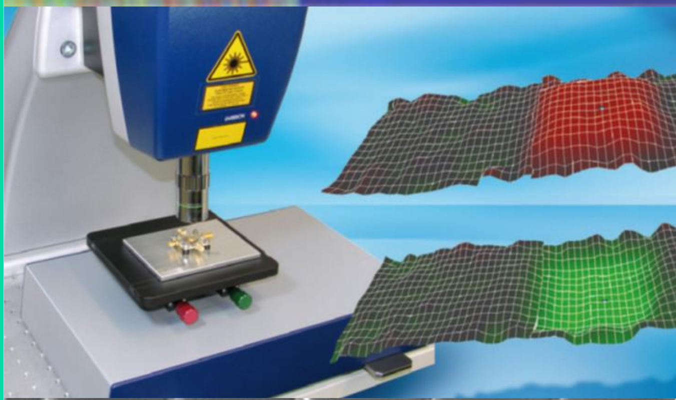
- Proof-of-principle simulation demonstrates that it is possible to engineer the dispersion characteristics of a local resonator array
- In turn, this allows tuning of the streaming jet
- Frequency-tuneable microfluidic and lab-on-a-chip devices could create new approaches for:
  - microfluidic mixing, SAW swimming, and nanoparticle manipulation

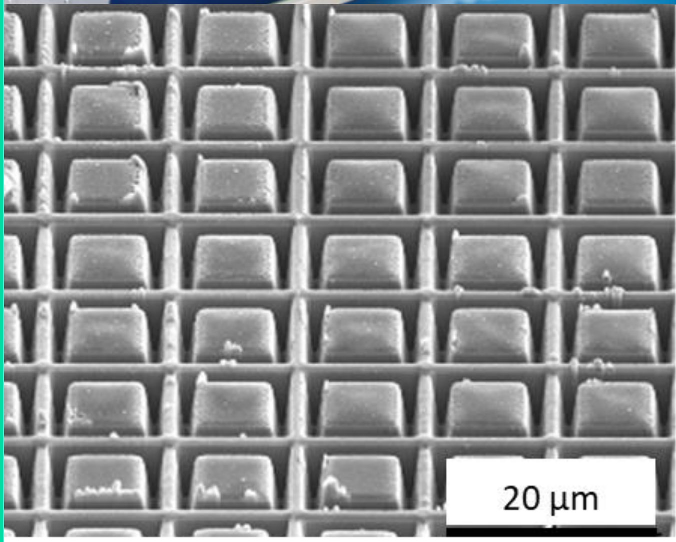


C Pouya and G R Nash, *"Metamaterial control of the surface acoustic wave streaming jet"* J. Phys. D: Appl. Phys. **57,** 195303 (2024).

Conclusions and Outlook







Conclusions and Outlook

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- Realising tuneable / active phononic crystals for SAWs is extremely challenging
- Arrays of consisting of *local resonators* have been shown to offer greater design freedom:
  - Bandgap frequencies and other characteristics are defined not only by the periodicity of the phononic crystal, but also by the properties of the resonators themselves
- Same principles can be applied across different length scales
- So far have not really designed structures that makes best use of the resonators
  - coupling of the resonators? What is a metamaterial?
- My research, which is largely curiosity driven, often doesn't seem to progress in a straight line!

Acknowledgements

University of Exeter

- Sophie Worsfold, Pete Vukusic, Kate Hoggard, Sophie Gossage, Tim Poole, Amgad Rezk, Leslie Yeo

- Ben Ash and Caroline Pouya

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Any Questions?

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