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Ultrasonic Communication Through a Metallic Barrier: Transmission Modeling and Crosstalk Minimization

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Outline

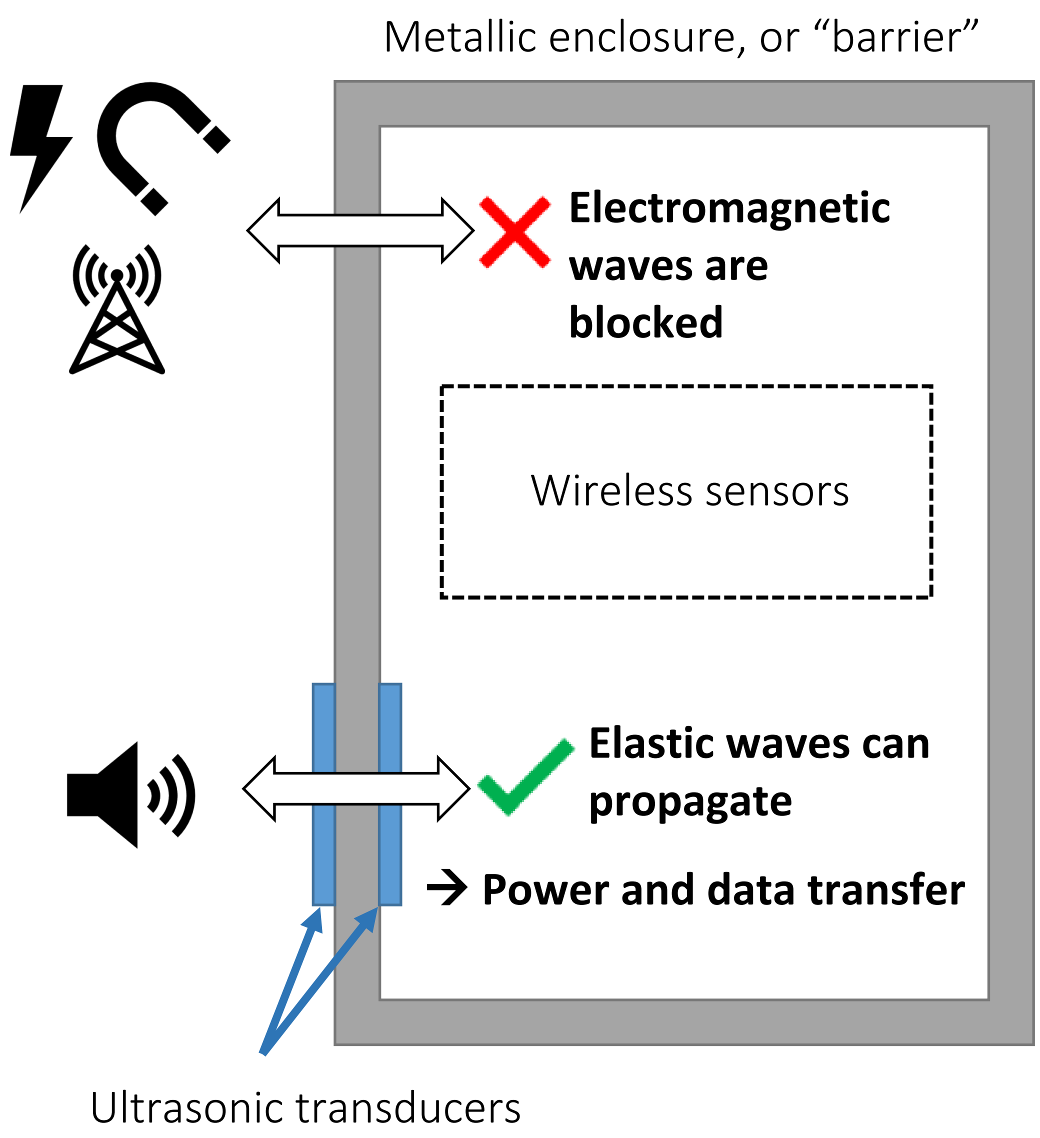
- Background and motivation
- Direct transmission of acoustic waves
- Electromechanical crosstalk
  - Guided wave propagation
  - Crosstalk minimization through transducer layout
  - Machined phononic crystals
- Conclusions

Mechanical Communication

- Many engineering applications in harsh environments require complete metal enclosures, which block transmission of electromagnetic waves.

- To supply power and send/receive data into such enclosures, traditional electromagnetic techniques fail.

- **Solution:** Transmit and receive signals carried by **elastic waves** excited by piezoelectric transducers bonded to the barrier.



Acoustic Data and Power Transfer

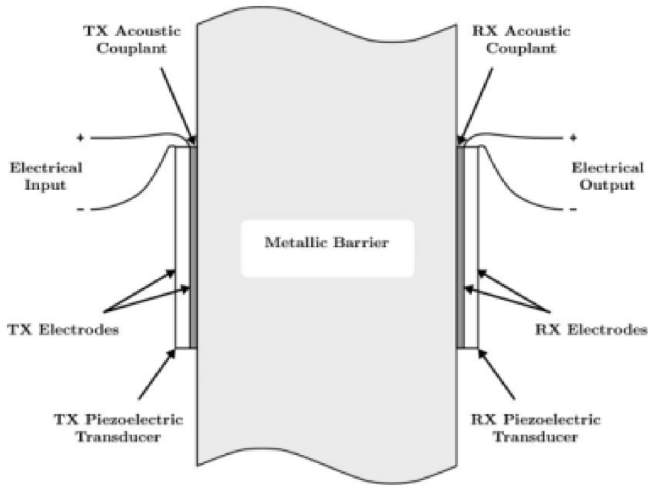


Fig. 1. Cross-section of the acoustic-electric channel (layers are not to scale).

Lawry, Tristan J., et al. "A high-performance ultrasonic system for the simultaneous transmission of data and power through solid metal barriers." *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control* 60.1 (2012): 194-203.

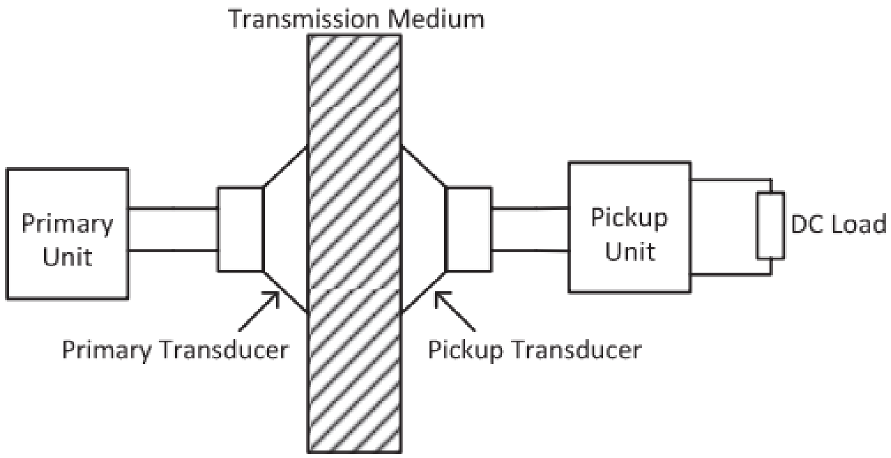


Fig. 1. Block diagram of developed AET prototype.

Leung, Ho Fai, Brett J. Willis, and Aiguo Patrick Hu. "Wireless electric power transfer based on Acoustic Energy through conductive media." *2014 9th IEEE Conference on Industrial Electronics and Applications*. IEEE, 2014.

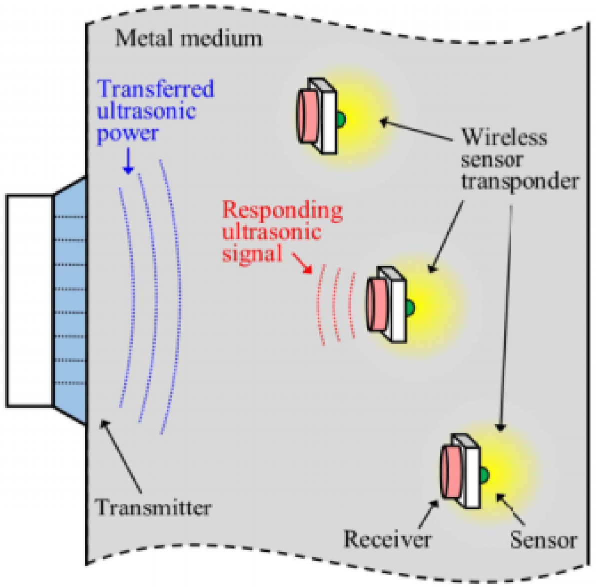


Fig. 1. Conceptual schematic of a wireless sensor network embedded within a solid metal structural piece for SHM, with power transfer and data acquisition achieved through ultrasonic waves.

Tseng, Victor Farm-Guoo, Sarah S. Bedair, and Nathan Lazarus. "Acoustic power transfer and communication with a wireless sensor embedded within metal." *IEEE Sensors Journal* 18.13 (2018): 5550-5558.

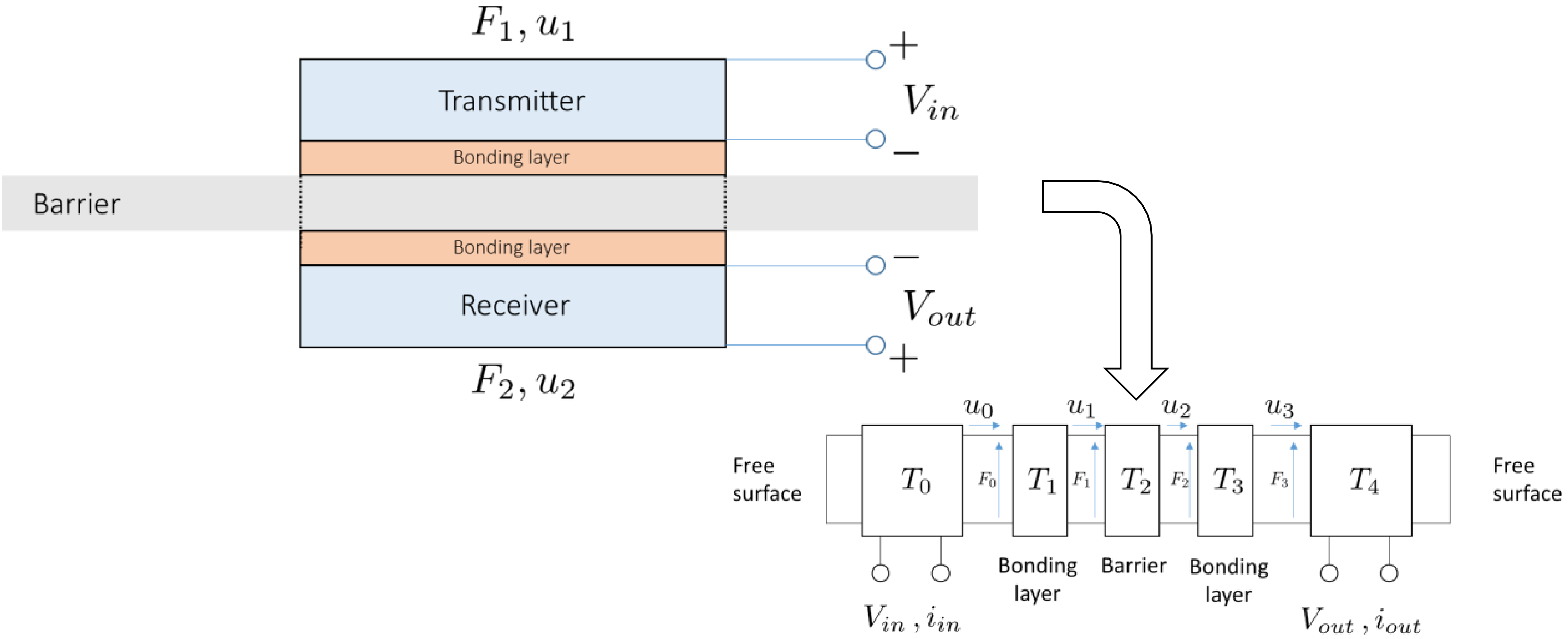
Elastic waves have been successfully used to supply power and transmit data

Objectives

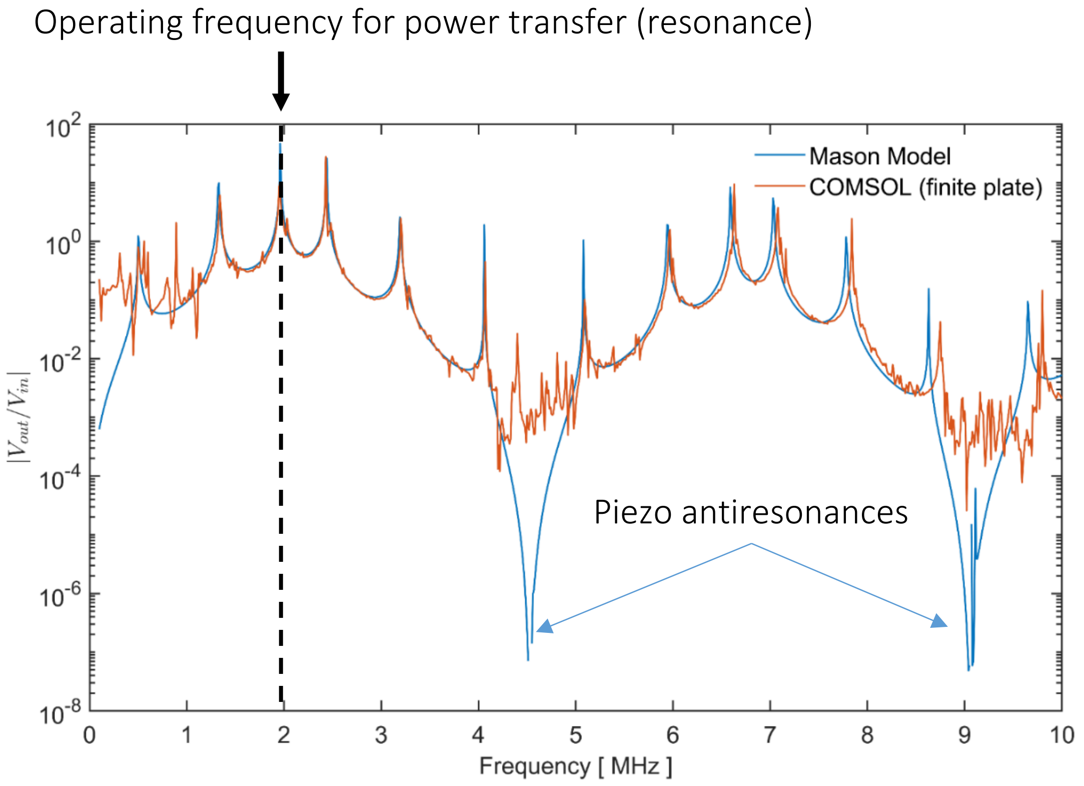
- Develop simplified models for mechanical communication channels comprising two piezoelectric transducers and an arbitrary sequence of layers.
- Explore electromechanical crosstalk between piezoelectric communication channels resulting from guided wave propagation in the barrier.
- Develop crosstalk reduction techniques to isolate individual power and data transmission channels.

Simplified Model: Single Channel

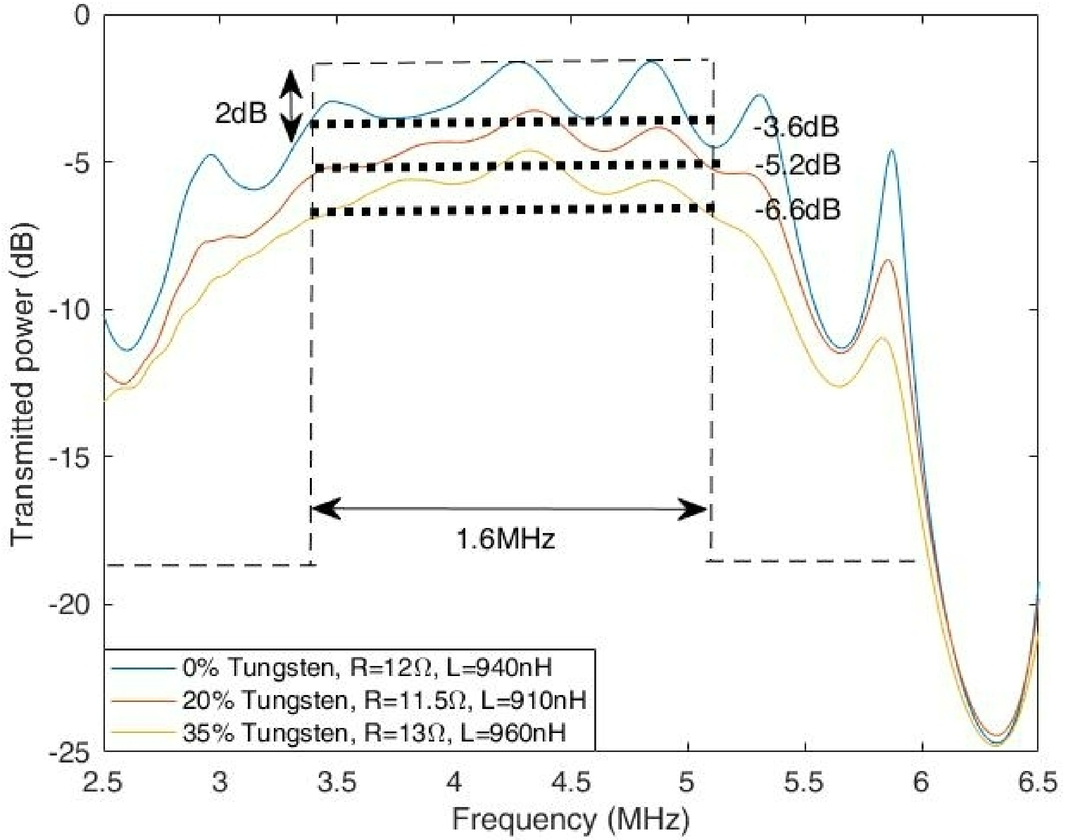
- Single transducer pair becomes a two-port electrical network:



Simplified Model: Typical Performance



Power transfer: Resonant operation at fixed frequency



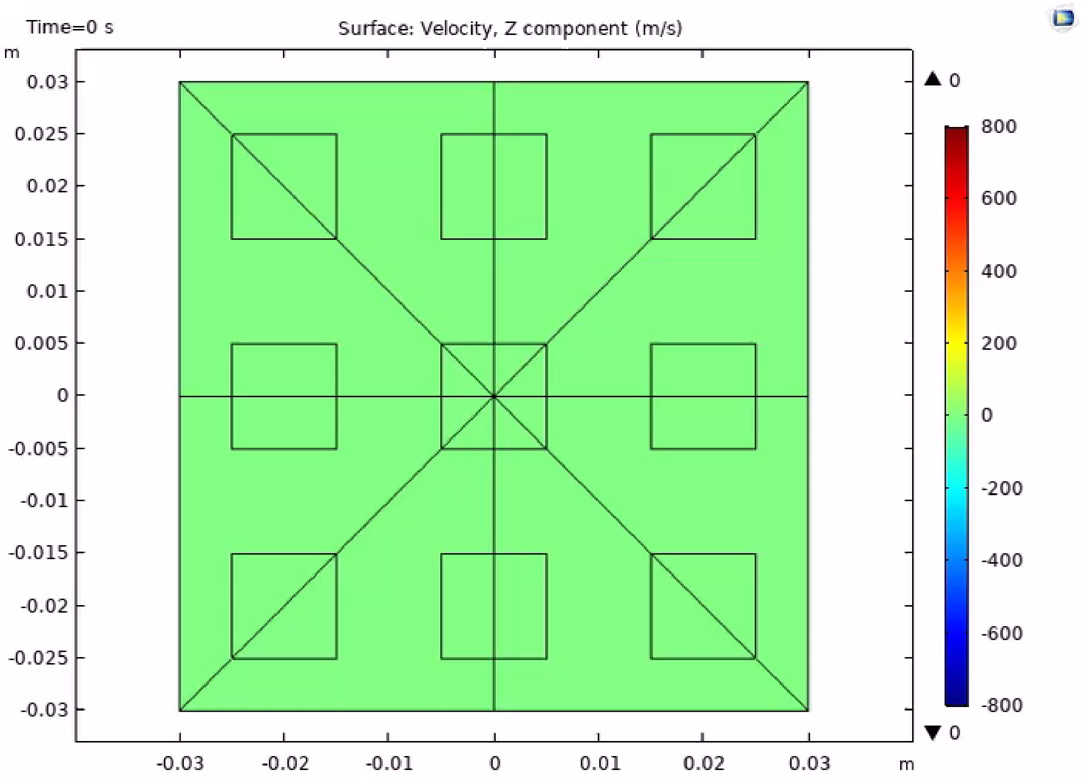
Data transfer: Flat bandwidth using mechanical backing and optimized resistor/inductor

Electromechanical Crosstalk

- The use of elastic waves to transmit energy introduces an additional source of crosstalk between data/power channels – guided waves propagating in the barrier between tiles.

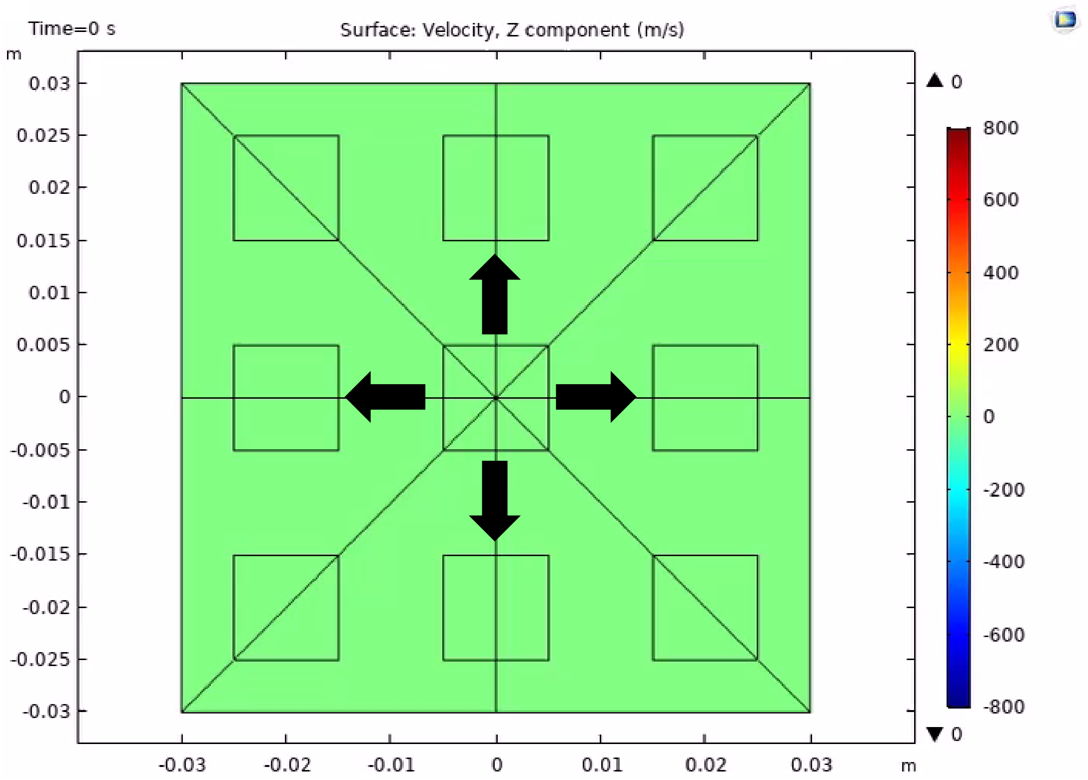
- Crosstalk can be generated by both power tile and data tile actuation.

- How can we reduce the crosstalk voltage received by a tile?



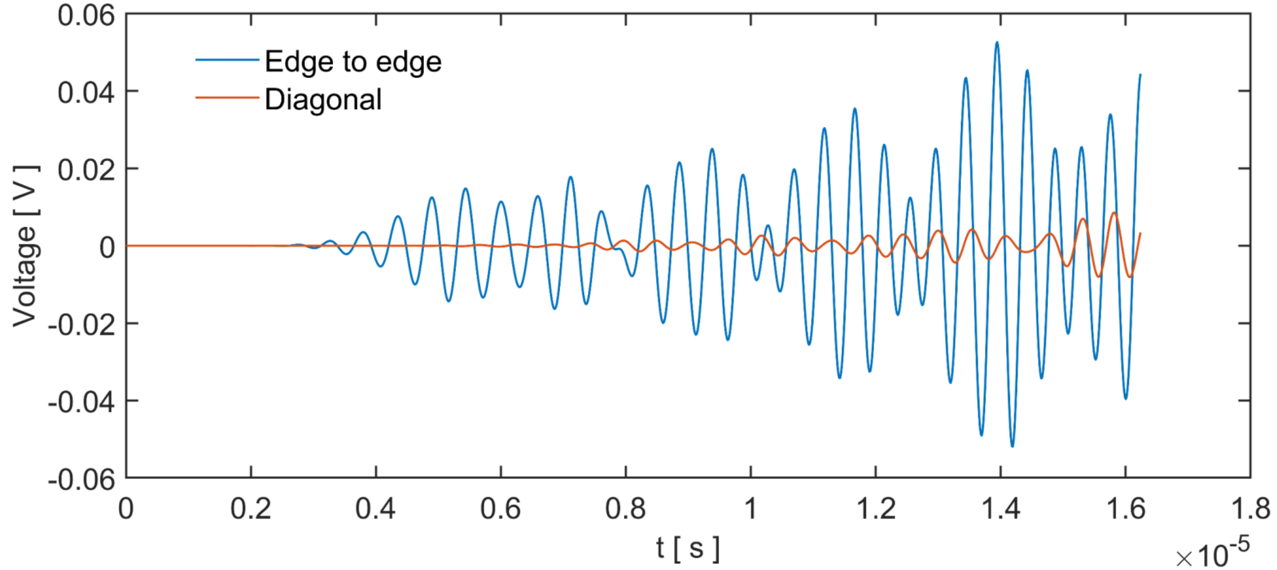
Crosstalk Directionality

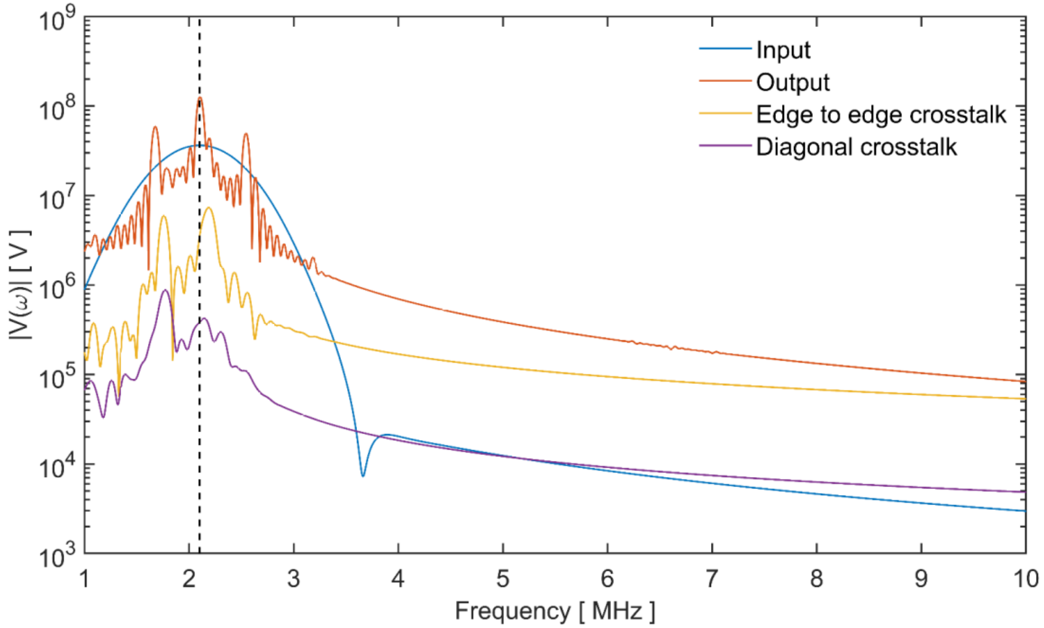
All tiles 1mm thick PZT-4



Placing tiles diagonally greatly reduces crosstalk

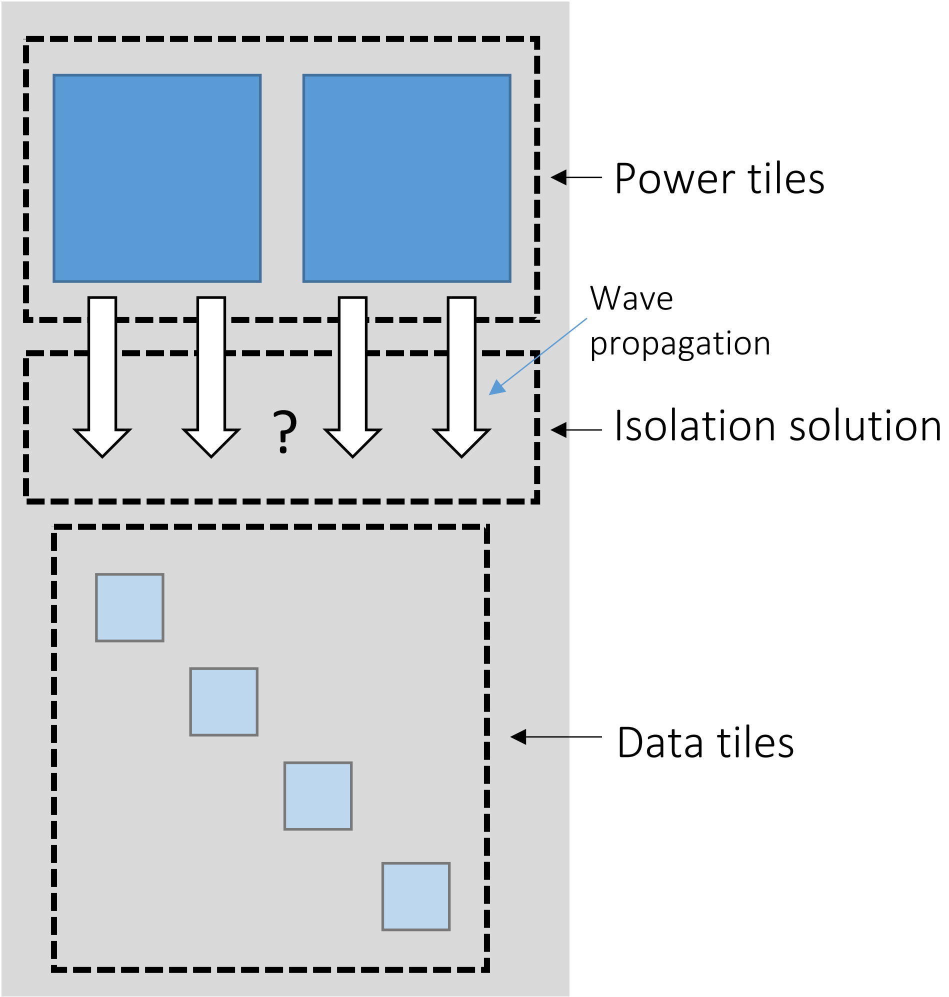
Crosstalk voltage





Power Tile Isolation

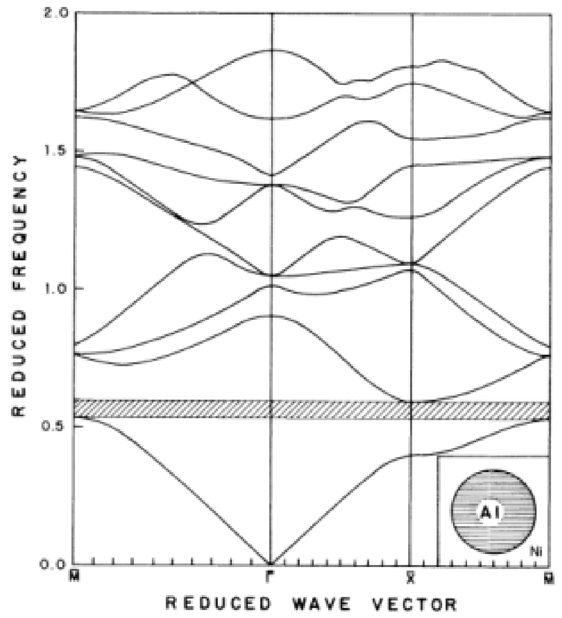
- Unlike data transmission, effective power transmission can be achieved over a very narrow frequency range (i.e. tiles operating at resonance).
- Crosstalk can be efficiently prevented by blocking the guided waves in the barrier that are generated at this frequency → **introduce a bandgap in the barrier at operating frequency**.
- Design challenge: barrier integrity must be maintained.



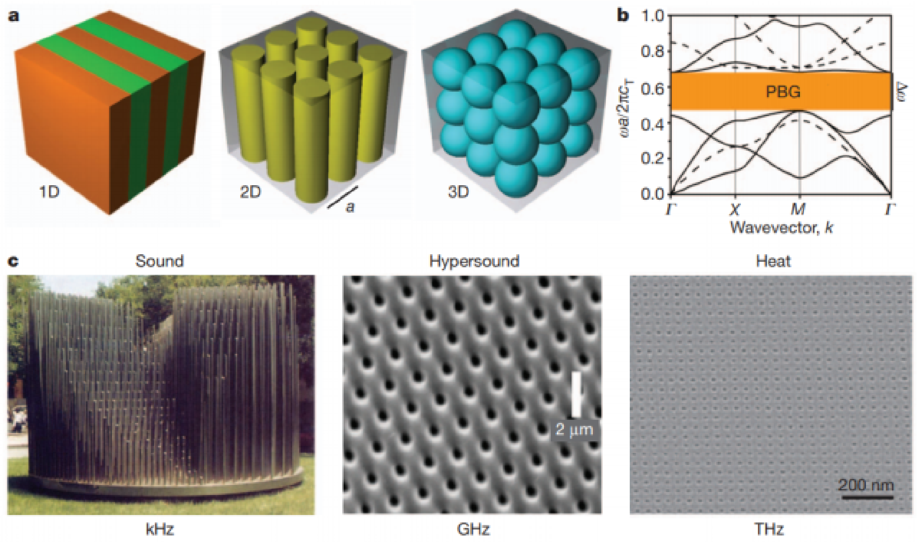
Grooving: Phononic Crystals and Bandgaps

- ***Phononic crystal (PC)***: periodic lattice or composite.
  - Capable of exhibiting *bandgaps*, other wave focusing/filtering properties.
- ***Bandgap***: frequency range where no waves can propagate.
- Challenging to design complete bandgaps for guided waves, which are multi-modal and highly dispersive (many wave modes at a certain frequency).

Kushwaha et al., 1993

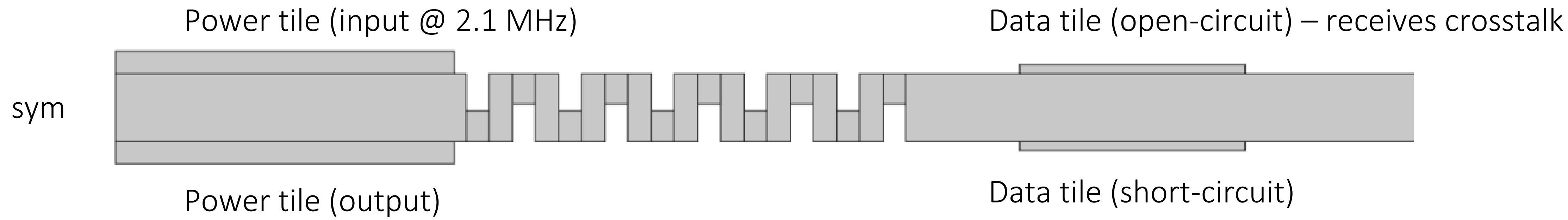


Maldovan, 2013



2D Finite Element Simulations

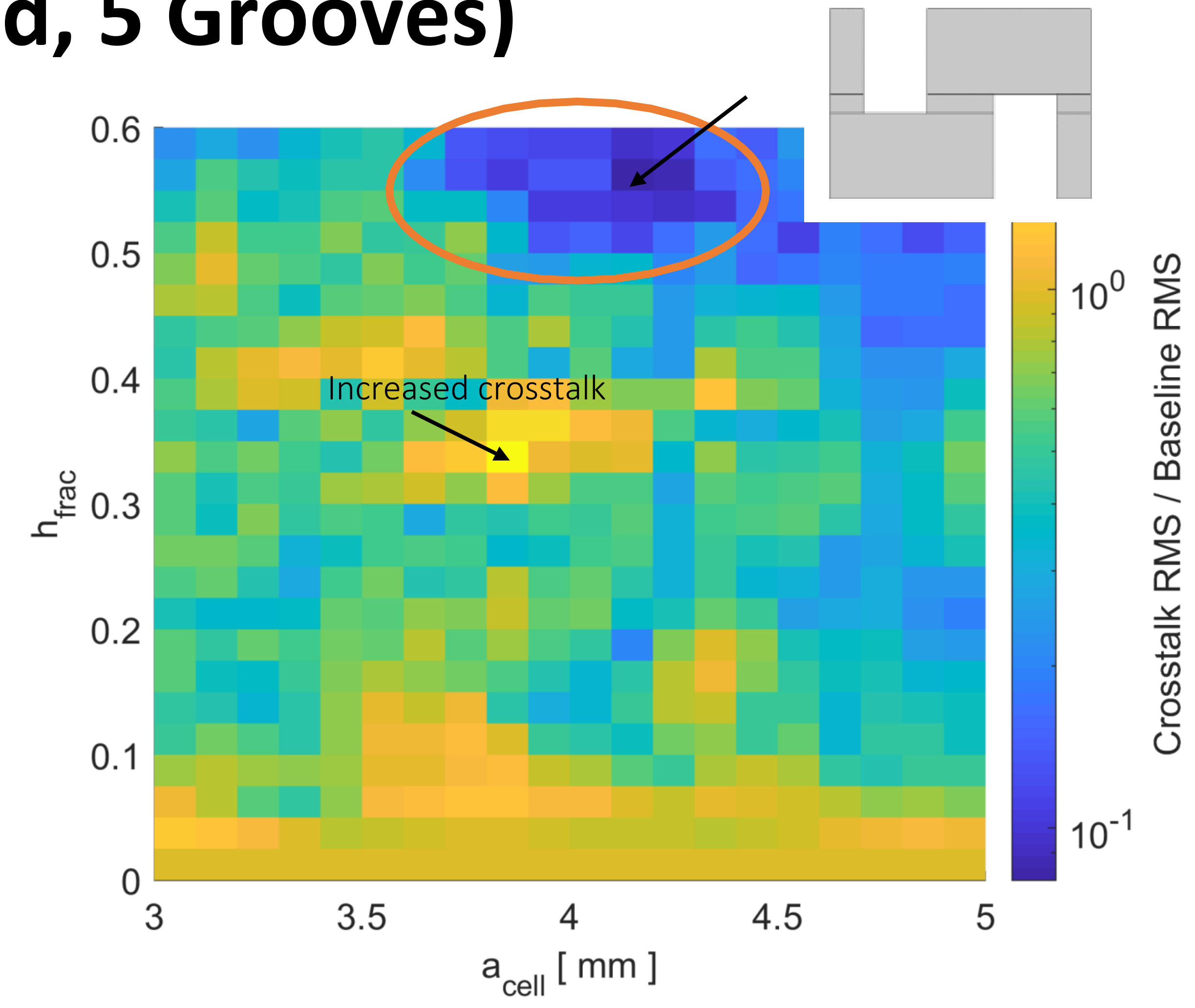
- Guided waves generated by power tiles are highly directional, wavefront is parallel to tile edge → 2D plane strain simulations capture behavior well.



- Fix groove width (limitation of machining tolerance), vary depth/spacing.

Crosstalk Reduction vs. Groove Depth and Spacing (Double Sided, 5 Grooves)

Deeper grooves



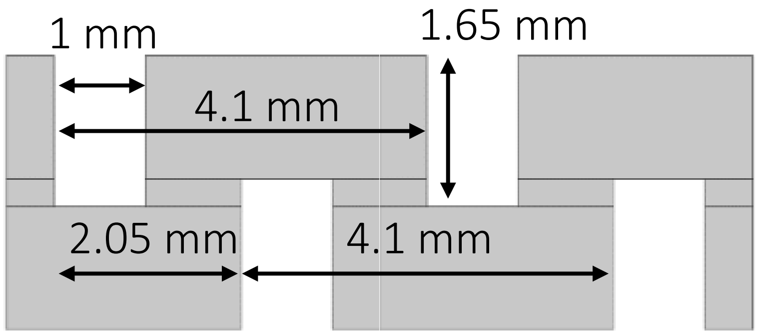
Greater distance between grooves

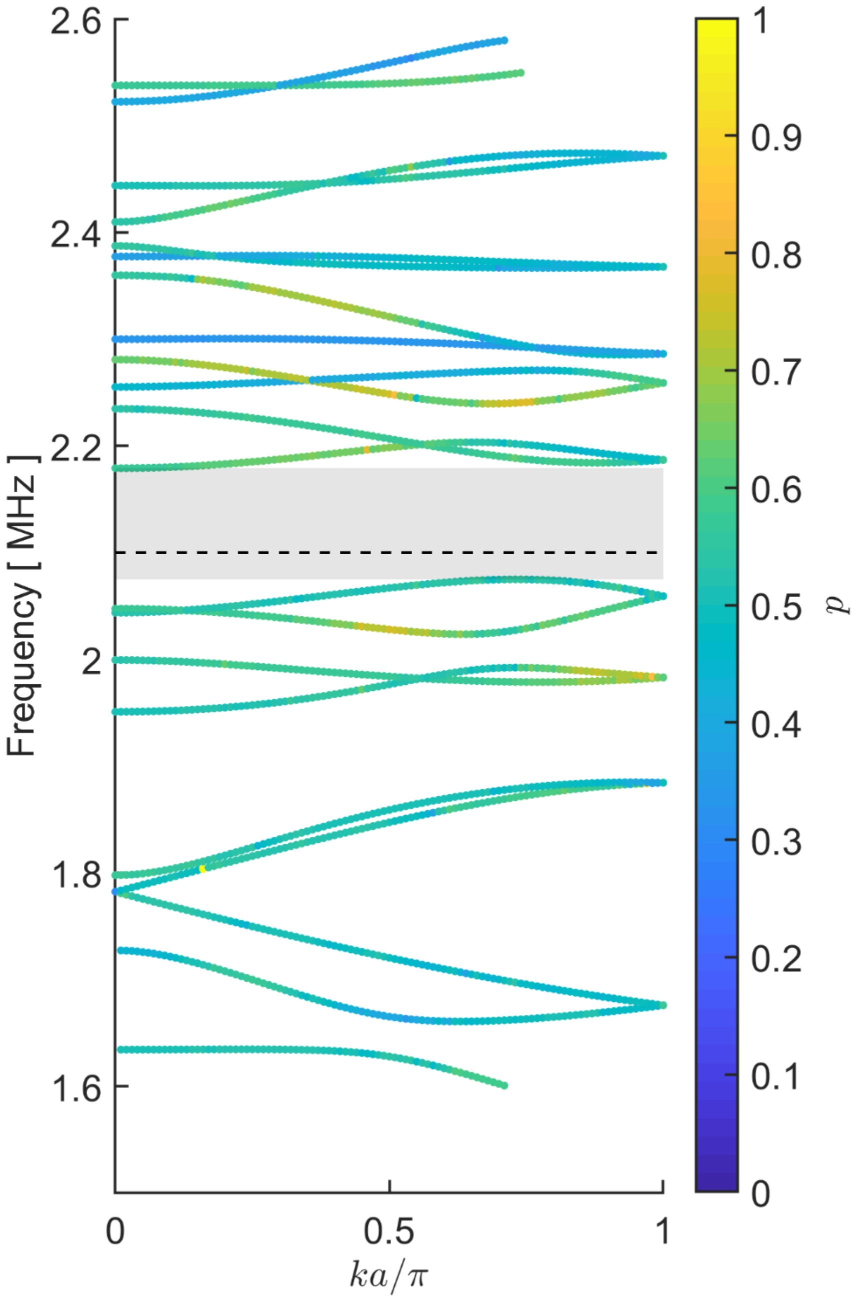
Best design (92% reduction in crosstalk):
4.1 mm unit cell
1.65 mm deep grooves

Design can tolerate variation in groove depth

Band Structure Analysis

- Dispersion describes wave propagation through the grooved region of the barrier.
- Weighting $$p = \int_A \frac{|v|^2}{|u|^2 + |v|^2} dA$$
  - Describes polarization of wave, large p → mostly out of plane motion
- Best-performing design shows bandgap at operating frequency.





Conclusions

- Using multiple mechanical communication channels on a single barrier generates crosstalk between channels arising from guided wave propagation.

- Crosstalk can be minimized using square tiles and avoiding edge-to-edge adjacency.

- Machining periodic grooves into the barrier can significantly reduce the level of crosstalk at a given frequency, while maintaining structural/electromagnetic integrity.

Questions?