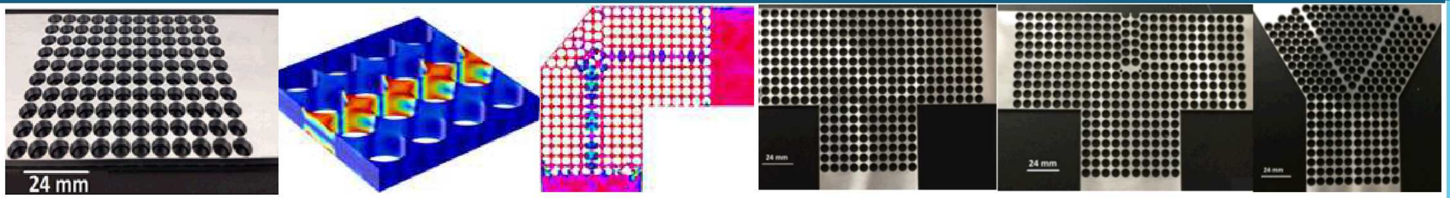
SAND2019-6231C

Demonstration of Waveguiding, Bends, Splitters in Macro-Scale Phononic Crystal Devices



PRESENTED BY

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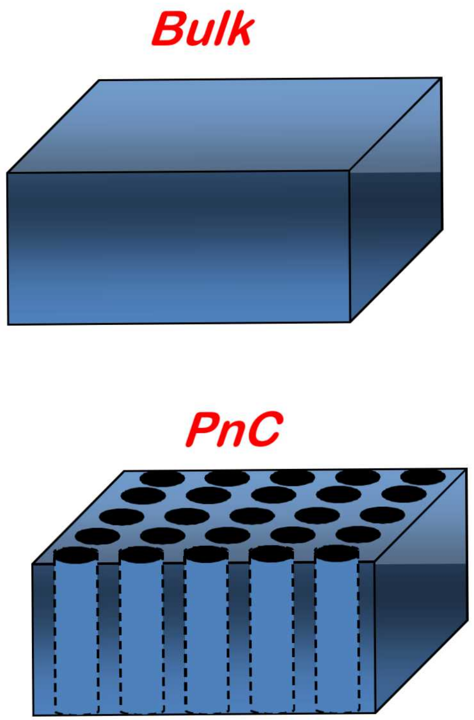
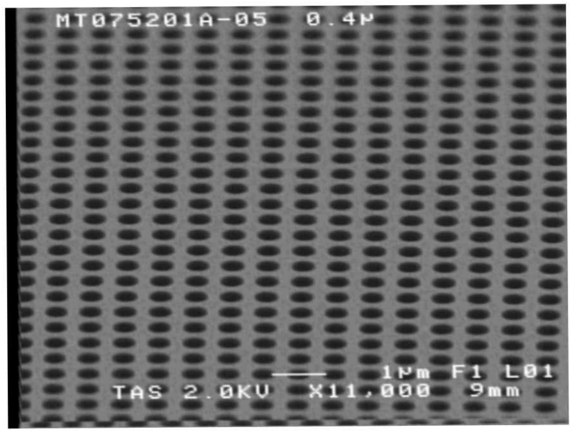
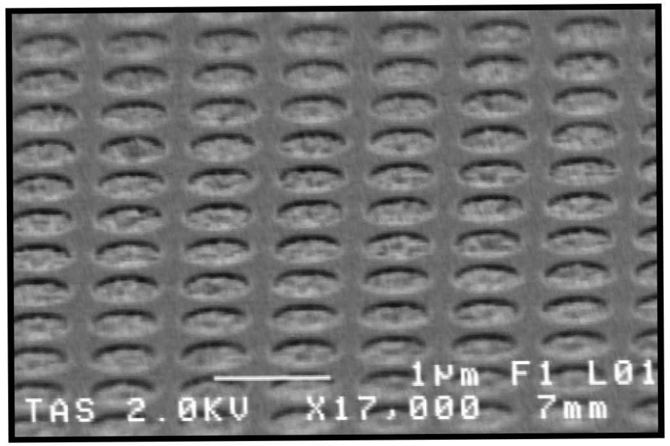
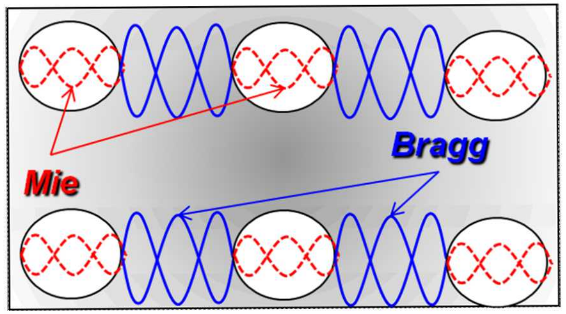
Phononic Crystals

- What is a Phononic Crystal (PnC)?
  - A periodic arrangement of two or more materials which exhibits anomalous dispersion for phonons
  - Can have bandgaps, i.e. frequency ranges in which phonon transmission in the material is prohibited
- How does a PnC Work?
  - Created by superposing Mie and Bragg resonant scattering by a periodic arrangement of scattering centers in a lattice
  - Requires sufficient acoustic impedance mismatch
  - Provides macro-to-micro scalable (N+1)D control (2D lattice ➔ 3D control) of the phonon distribution



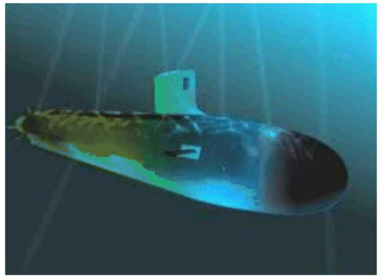






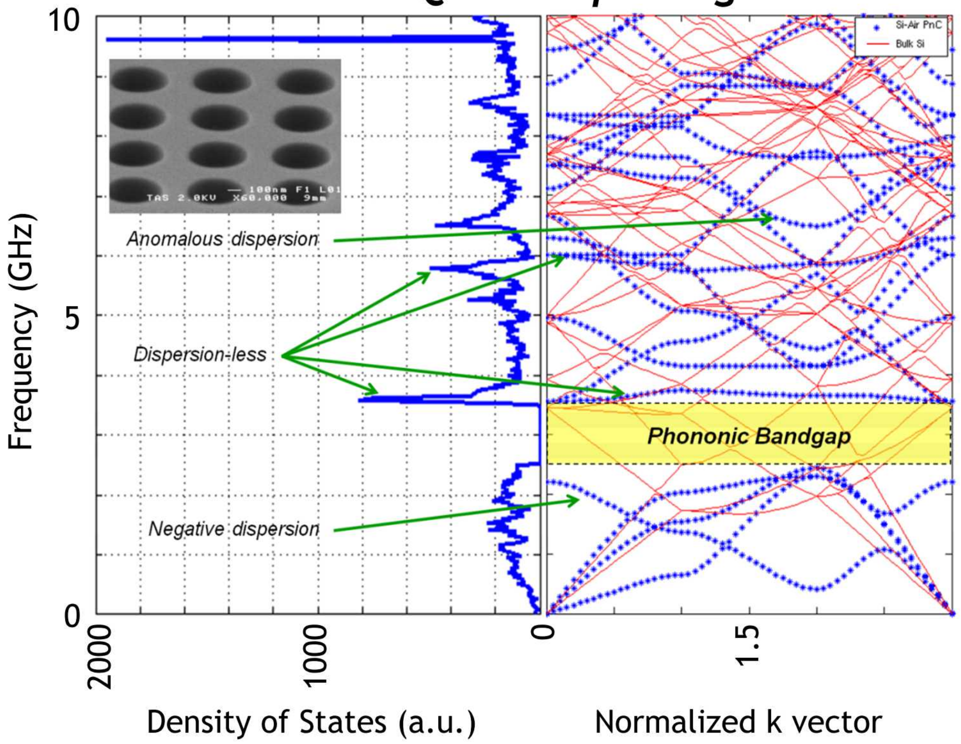
Applications of Phononic Crystals

- RF signal processing (filters, delay lines)
- Acoustic and ultrasonic applications
- High Q-factor Cavities
- Phonon density of states (DoS) manipulation
- Thermal conductivity engineering
- Frequency-selective vibration dampening



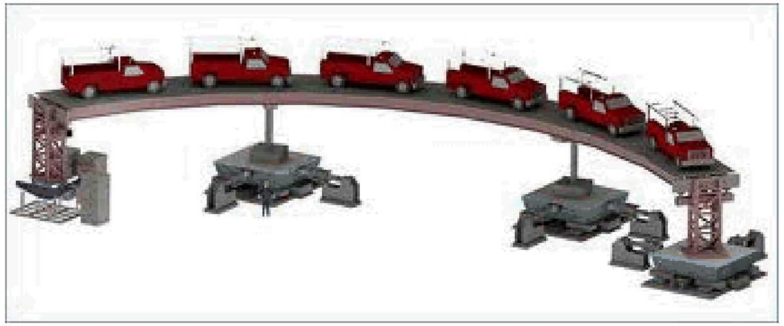
Underwater stealth

Quiet ship design



Phonon DoS engineering

Quiet engines



Earthquake Mitigation

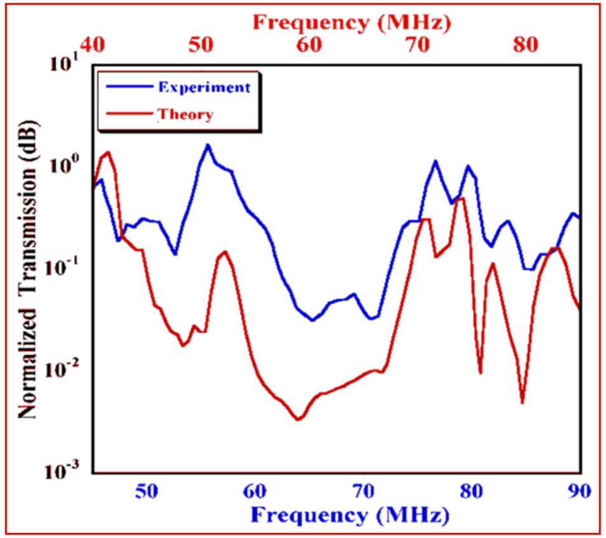
Quieter tires

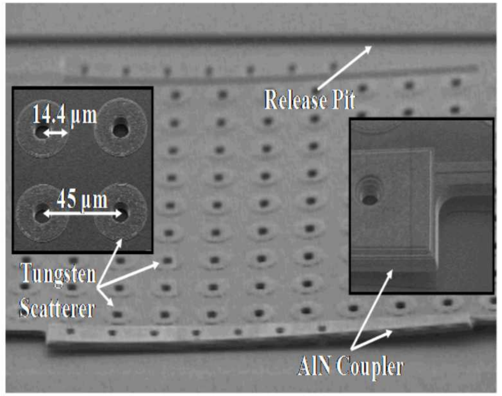
Vibration isolation

Signal Processing with Phononic Crystals

1st MHz MEMS PnC (VHF) 2008

MEMS

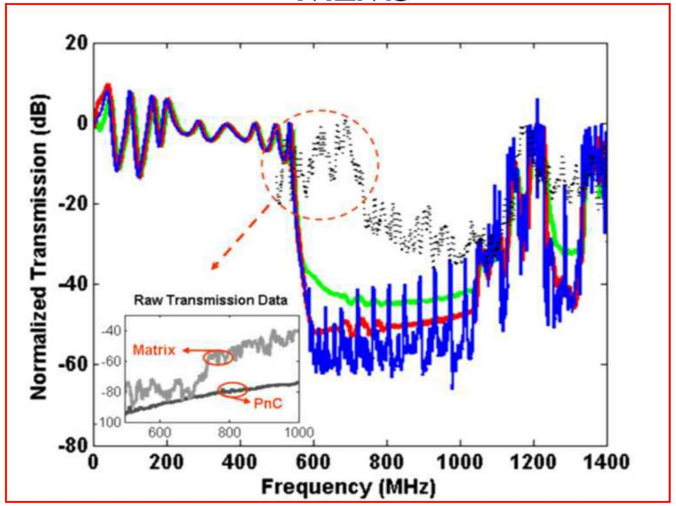


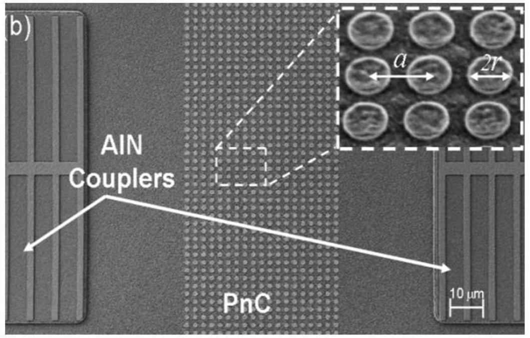


I. El-Kady, et.al., APL, 2008

1st GHz MEMS PnCs (UHF) 2009

MEMS

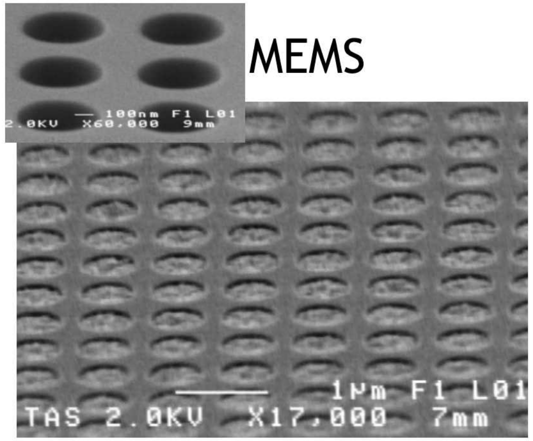




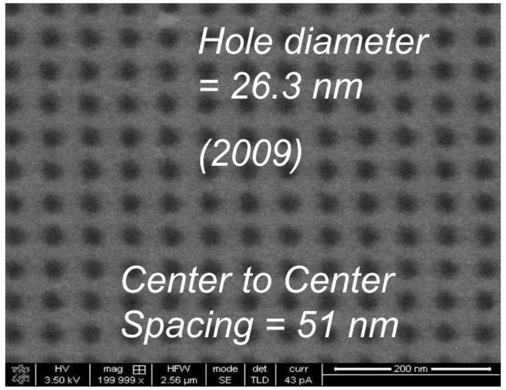
M. Su, et.al., APL, 2009

10 GHz PnCs (UHF) 2009

MEMS

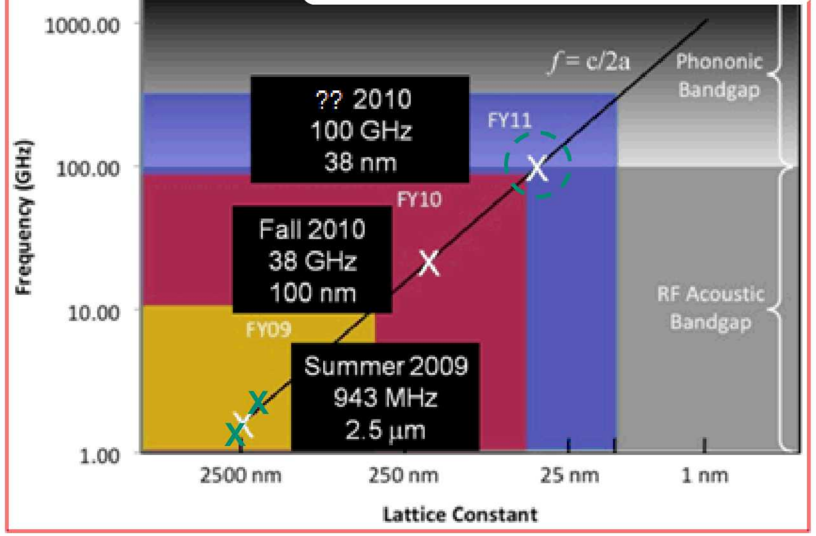


38 GHz PnCs (UHF) 2010



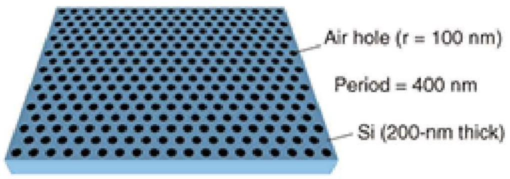
FIB

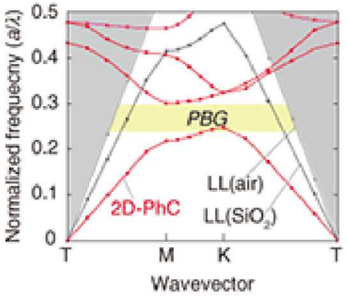
Moore's Law for PnCs

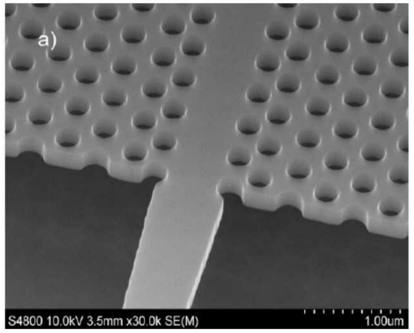


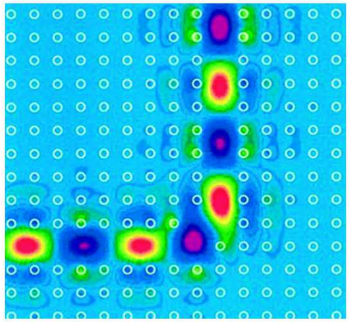
Mechanical Analogue to Photonic Crystals

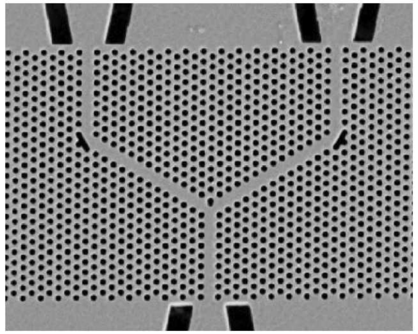
- Photonic crystals
  - Periodic refractive index mismatch
  - Manipulate photon propagation with periodicity of photon wavelength



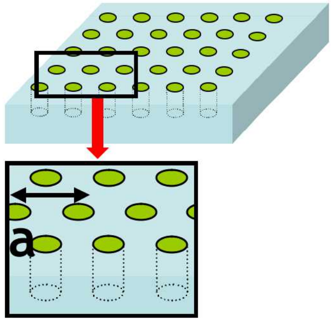


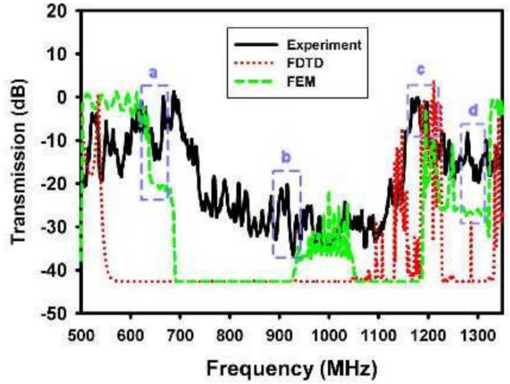






- Phononic crystals
  - Periodic mechanical impedance mismatch
  - Manipulate the propagation of elastic/acoustic waves with periodicity of the acoustic wavelength





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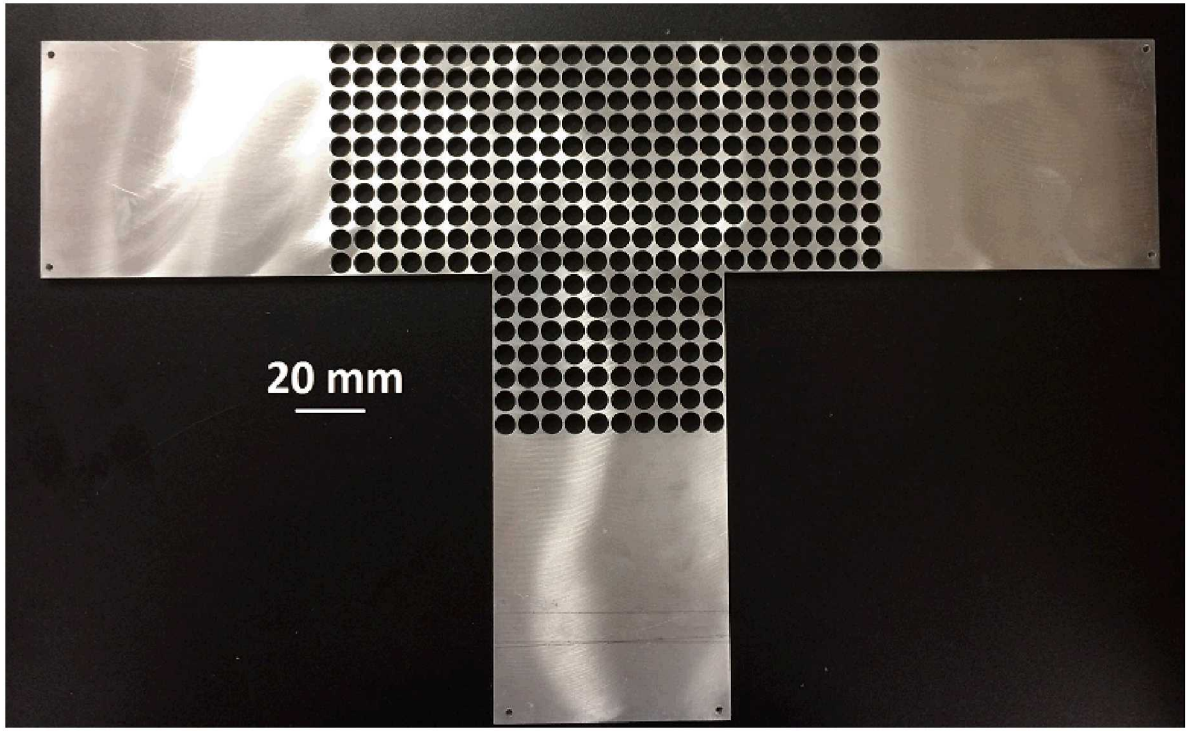
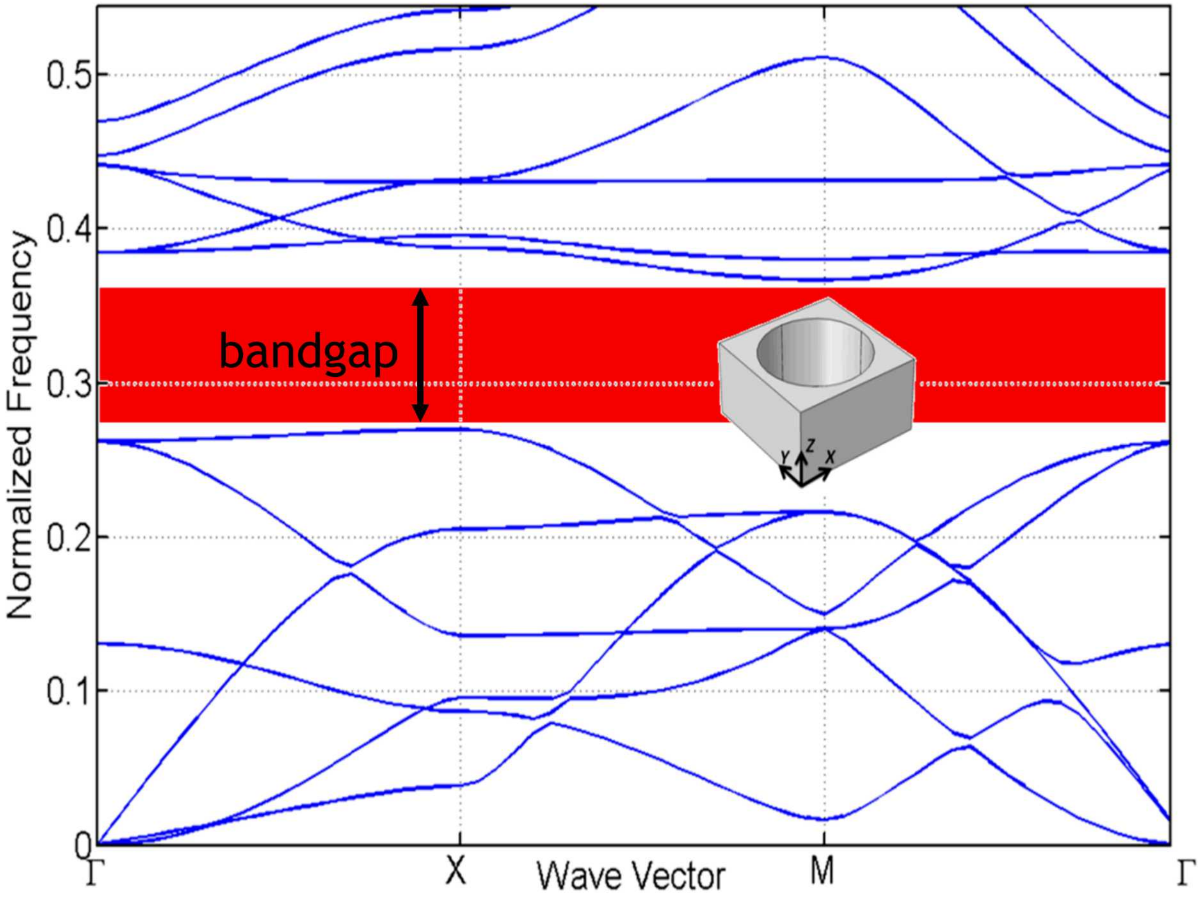
Macro-Scale Phononic Crystals

- Aluminum–air macro-scale PnC
  - Excellent machinability
  - Relaxed fabrication constraints
  - Rapid fabrication turn around
- Simple cubic lattice geometry
  - Able to achieve large bandgaps
- Simulations and measured results are scaled to the reduced frequency $\Omega = \omega a / 2\pi C_t$
  - ω is the angular frequency, C_t is the transverse sound velocity, and a is the lattice constant
  - Behavior scales directly to the micro-/nano-scale

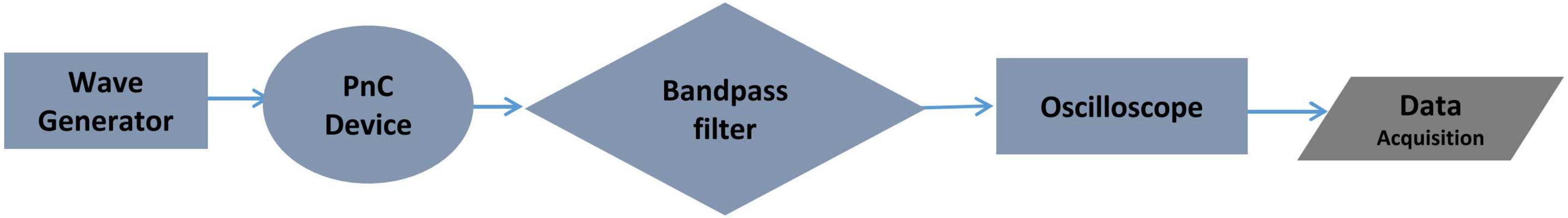


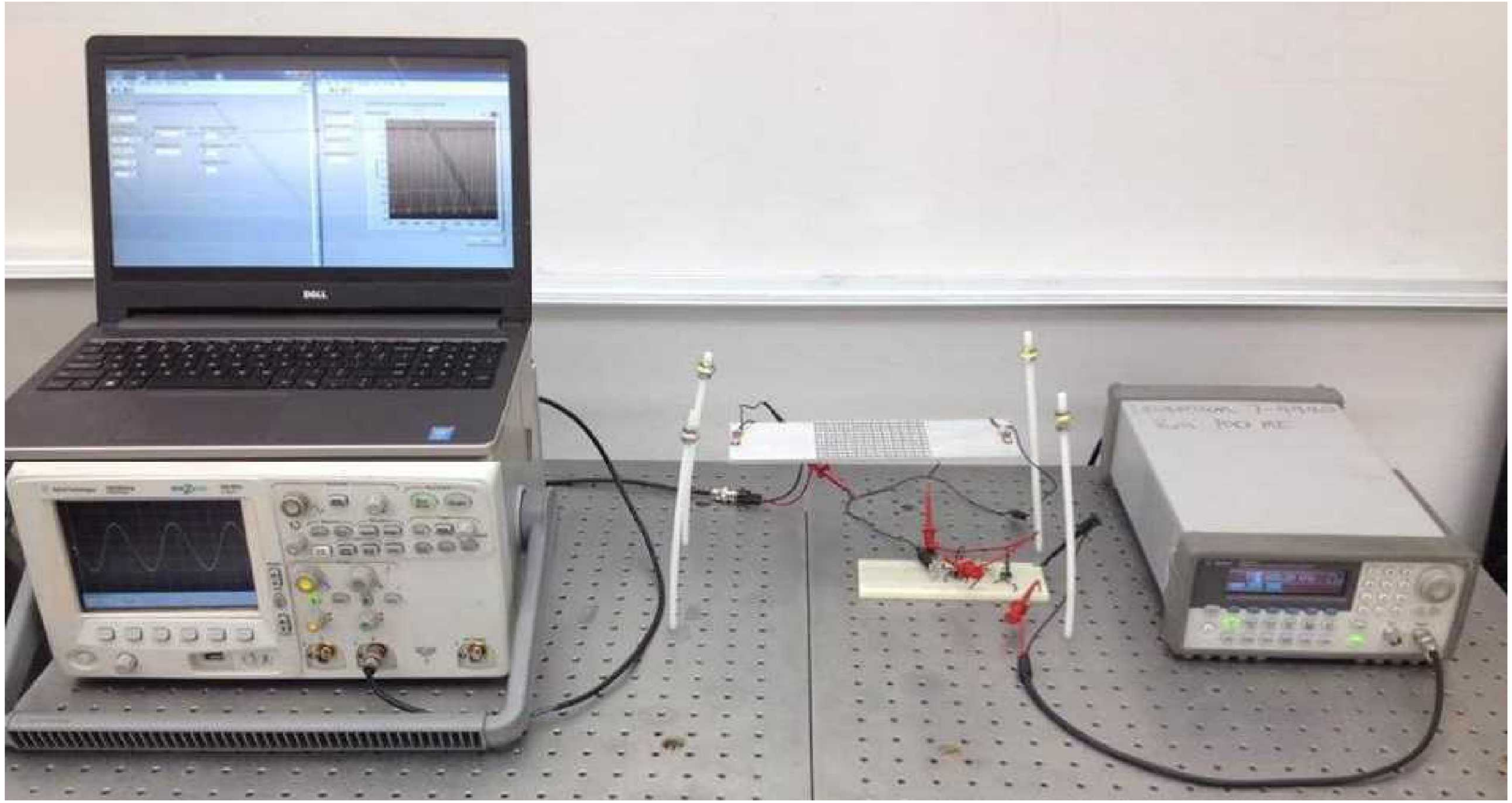
Phononic Crystal Design

- Material: Al
  - Lattice constant $a = 8$mm
  - Slab thickness $t = 4$mm ($t/a = 0.5$)
  - Hole radius $r = 3.84$mm ($r/a = 0.48$)
- Bandgap range :
  - Calculated bandgap for the full irreducible Brillouin zone from 149 – 202kHz, corresponding to 0.27 to 0.366 in normalized frequency
  - Gap-to-midgap ratio = 30%



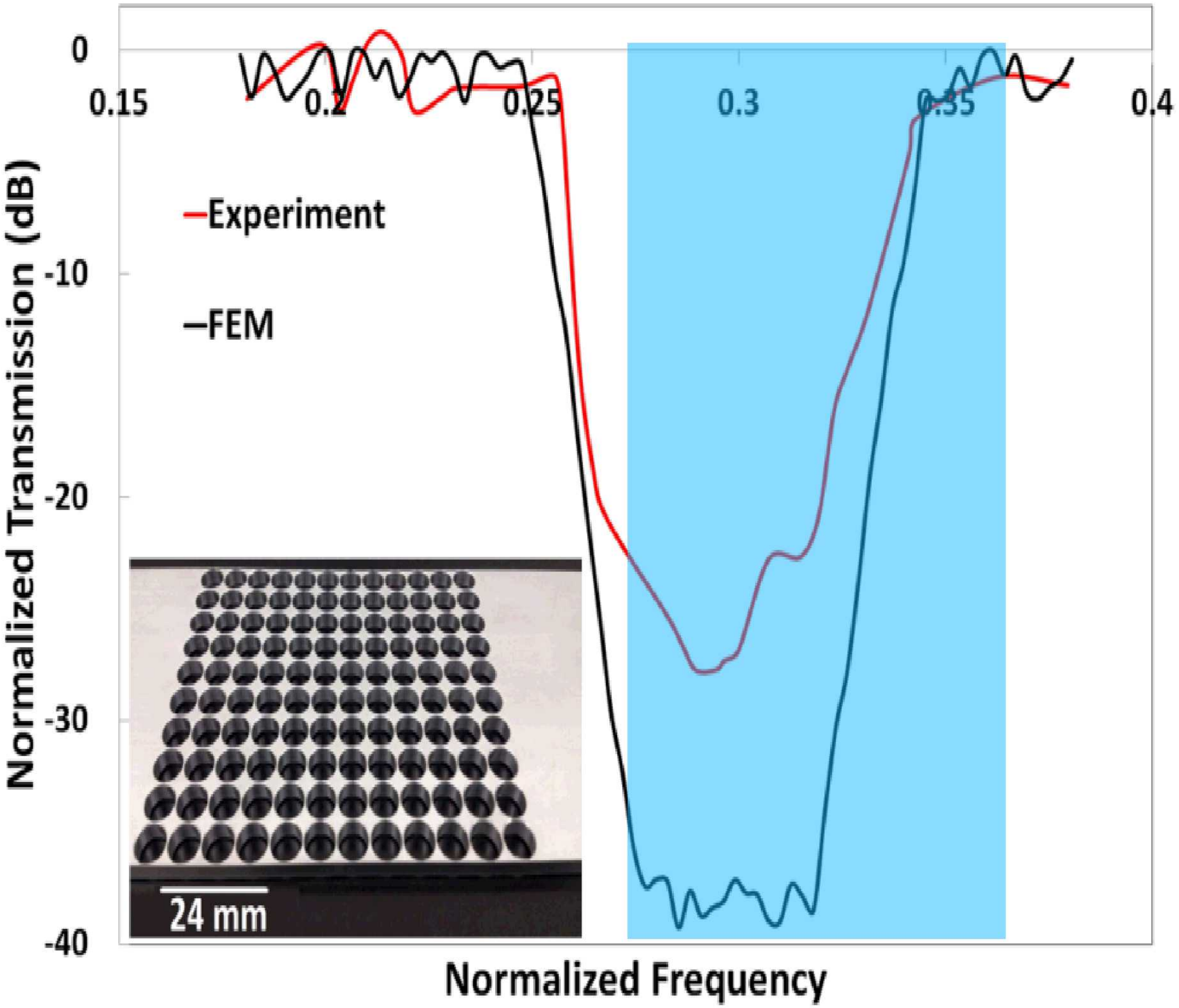
Experimental Setup





PnC Bandgap Characterization

- Measured transmission was normalized with slab (bulk Al with no holes)
  - Transmission is attenuated by >20dB in the frequency range $0.26 < \Omega < 0.34$
  - Agrees well with the theoretically predicted **$0.27 < \Omega < 0.366$**
- Finite-element method simulation used to verify the results
  - Difference due to fabrication imperfection and finite size of the fabricated sample

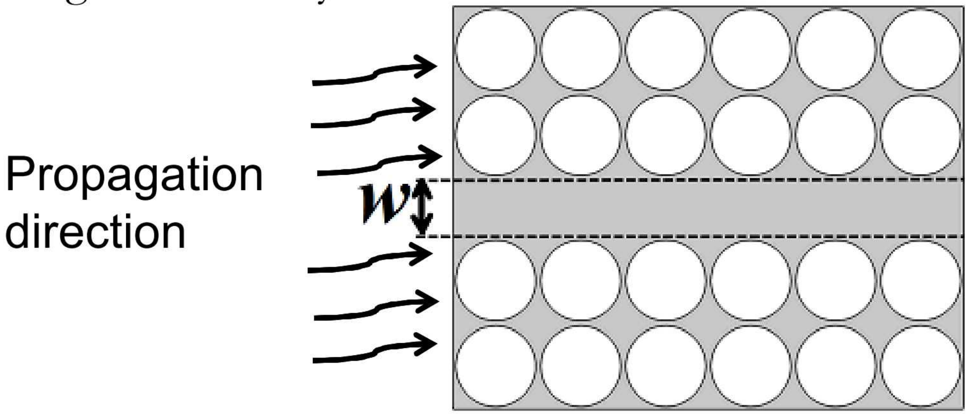


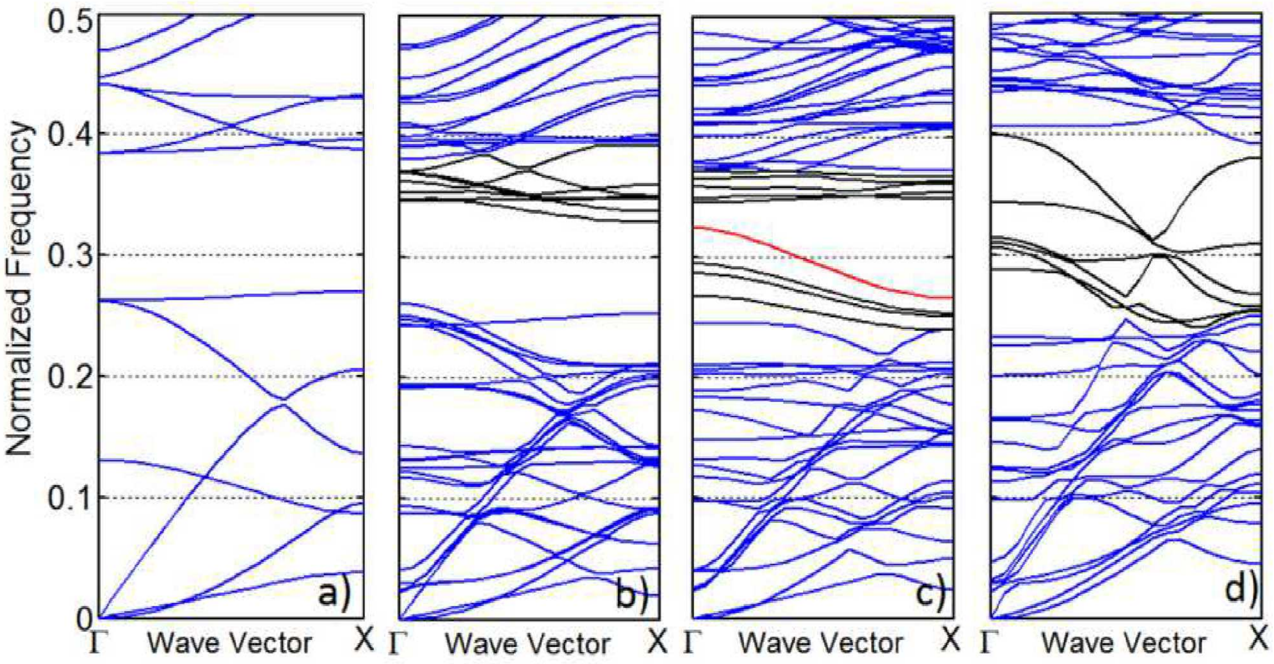
PnC Waveguide Design

- Waveguide created by introducing a line defect in the PnC along the propagation direction.
- The defect width is defined as:

$$w = (1+\alpha)\, a - 2r$$

  - $\alpha = 0$ corresponds to the perfect PnC (no defect)
  - $\alpha = 1$ corresponds to the so-called W1 waveguide
- The band structure was studied versus defect width
  - An isolated, single-mode waveguide was found for **α = 0.1**
  - Stronger confinement of the propagating energy ➔ higher efficiency





a) α = 0 (Perfect PnC)

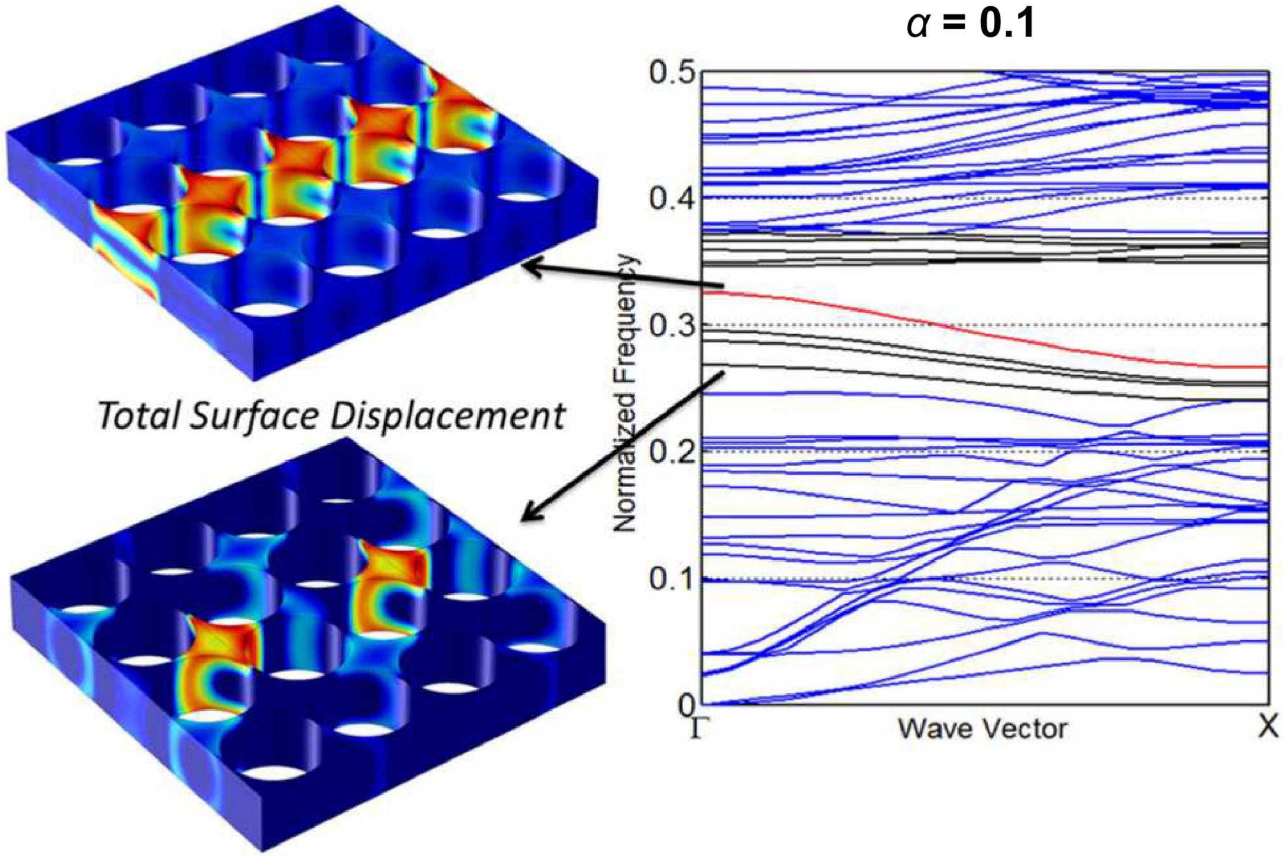
b) α = 0.01

c) α = 0.1

d) α = 0.5

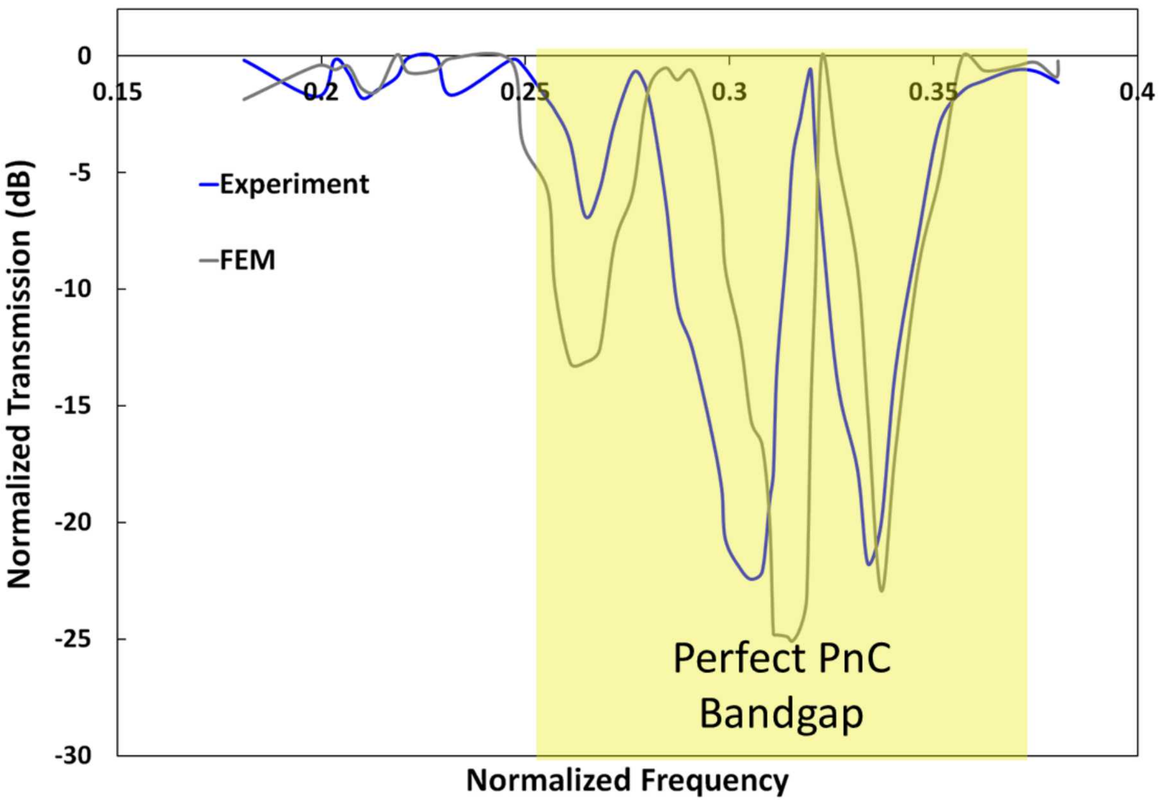
PnC Waveguide Design

- The modes indicated in black and red result from the introduction of the line defect
- The lower-frequency mode is leaky
  - Energy propagates throughout the crystal and is not strongly guided
- The higher-frequency mode is a guided mode
  - Energy is well-confined
  - Waveguide is single-mode from about $0.3 < \Omega < 0.32$



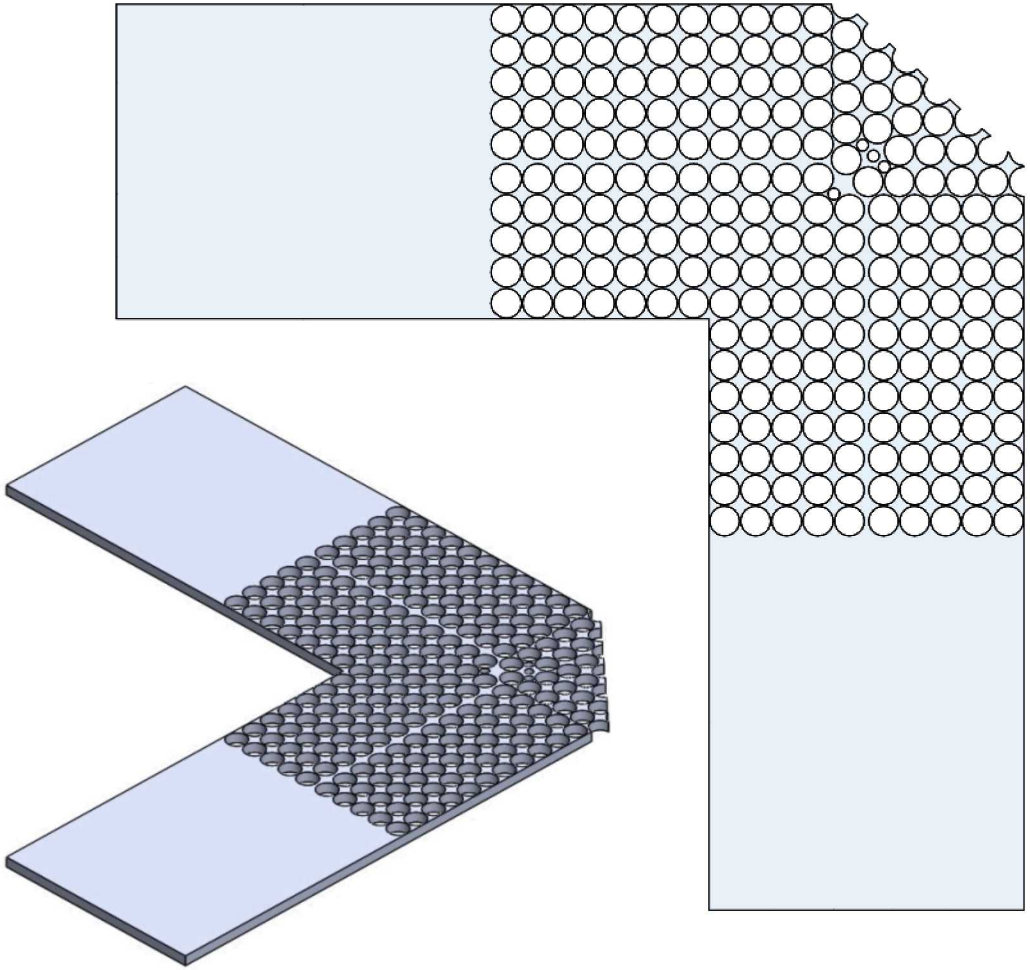
PnC Waveguide Characterization

- Passband measured within the bandgap from $0.25 < \Omega < 0.287$
- Transmission peak is centered at 0.32 in normalized frequency (177kHz) with only 1dB loss
- Disagreement in peak frequency between measurement and simulation is less than 2%
  - Discrepancy attributed to the difference between theoretical and actual material properties



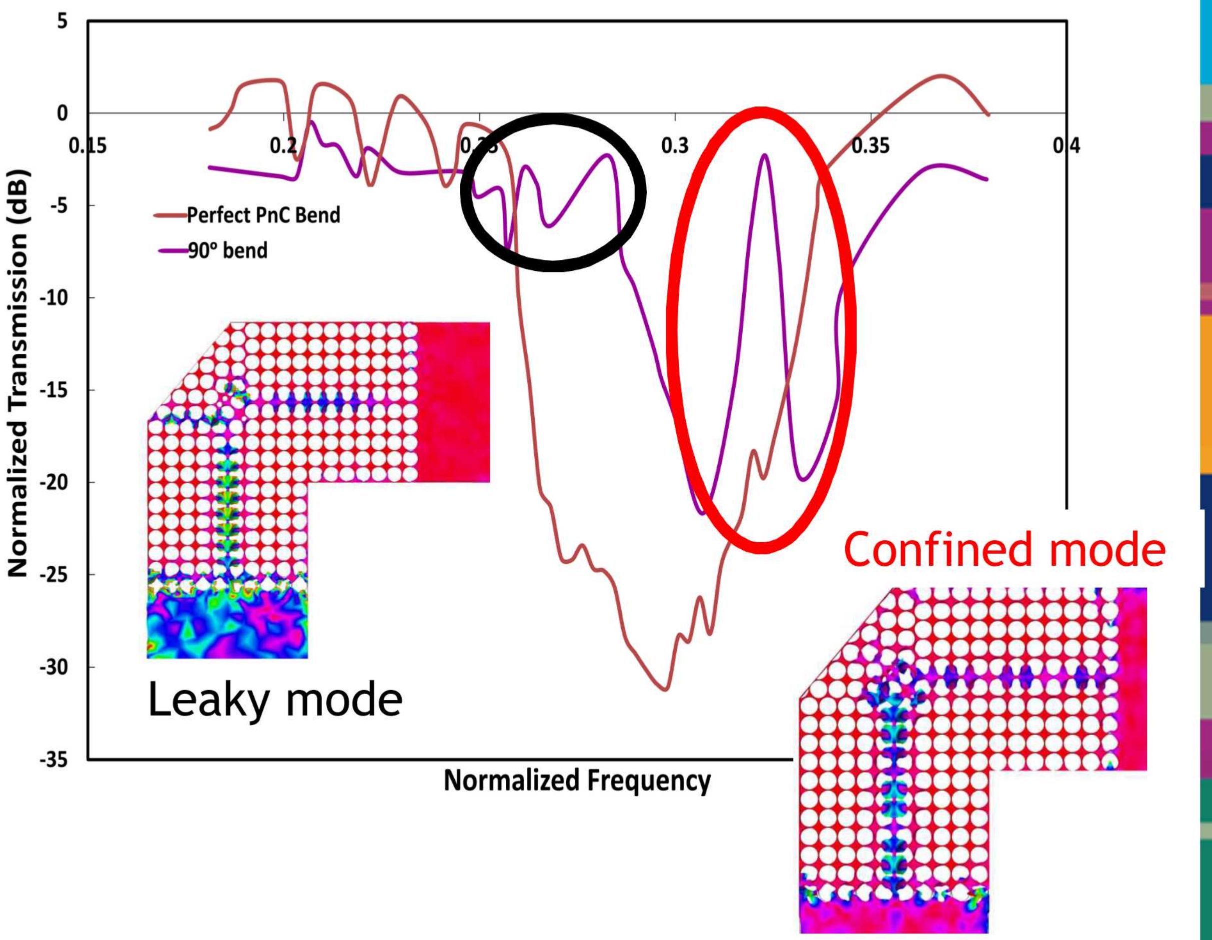
PnC Bent Waveguide Design

- A 90° bent waveguide was designed and fabricated with $\alpha = 0.1$
  - Lattice was slightly perturbed in the bend region by the introduction of reduced-size holes
  - The size of the small holes were chosen to maintain the critical dimension (minimum hole separation distance)
  - A 45º chamfer angle was introduced at the outer edge of the bend



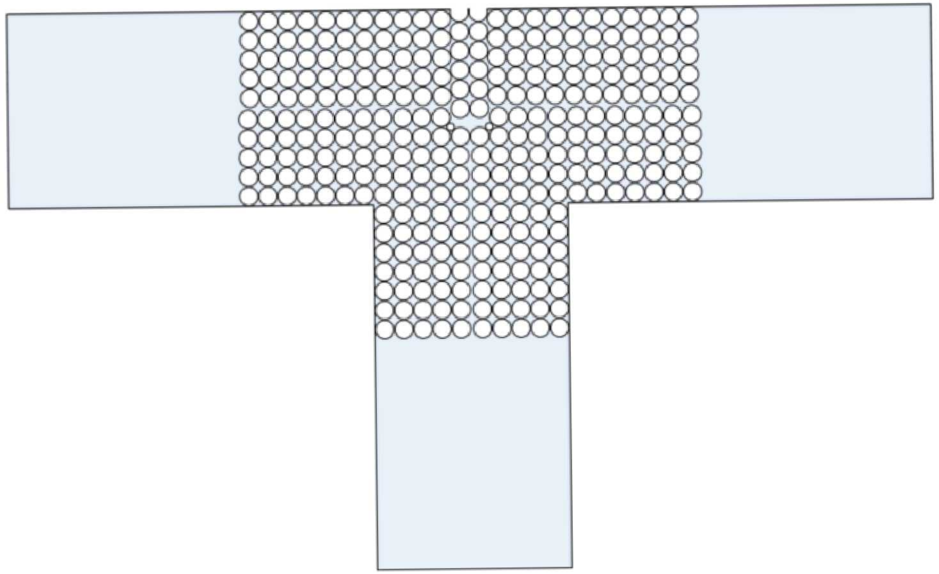
PnC Bent Waveguide Design

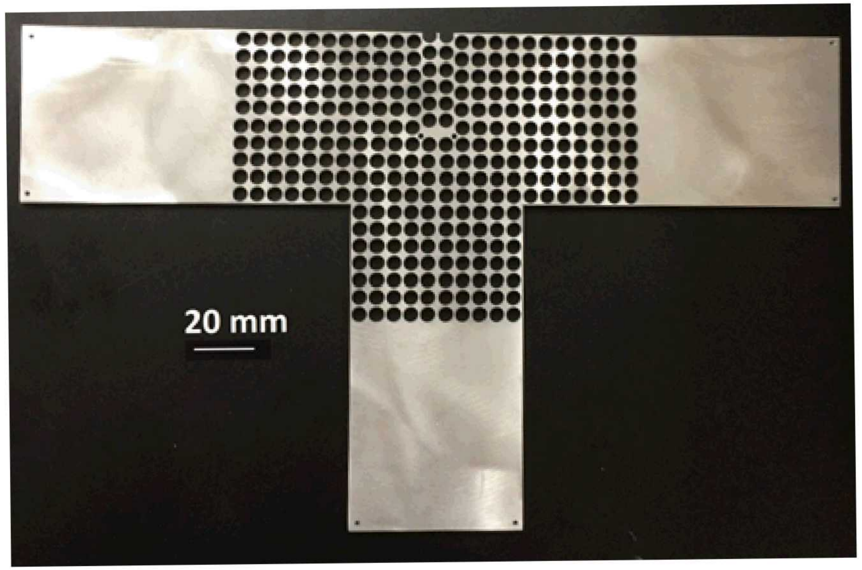
- Similar to the straight waveguide, the lower-frequency mode is not well-localized and mostly reflects back into the input
- The higher-frequency mode at Ω=0.32 is well-localized
  - The incident wave propagates couples efficiently in the perpendicular direction.
- Measured transmission coefficient of the bent waveguide = -2.3dB
  - Corresponds to 76% energy transmission efficiency



PnC T-Splitter Design

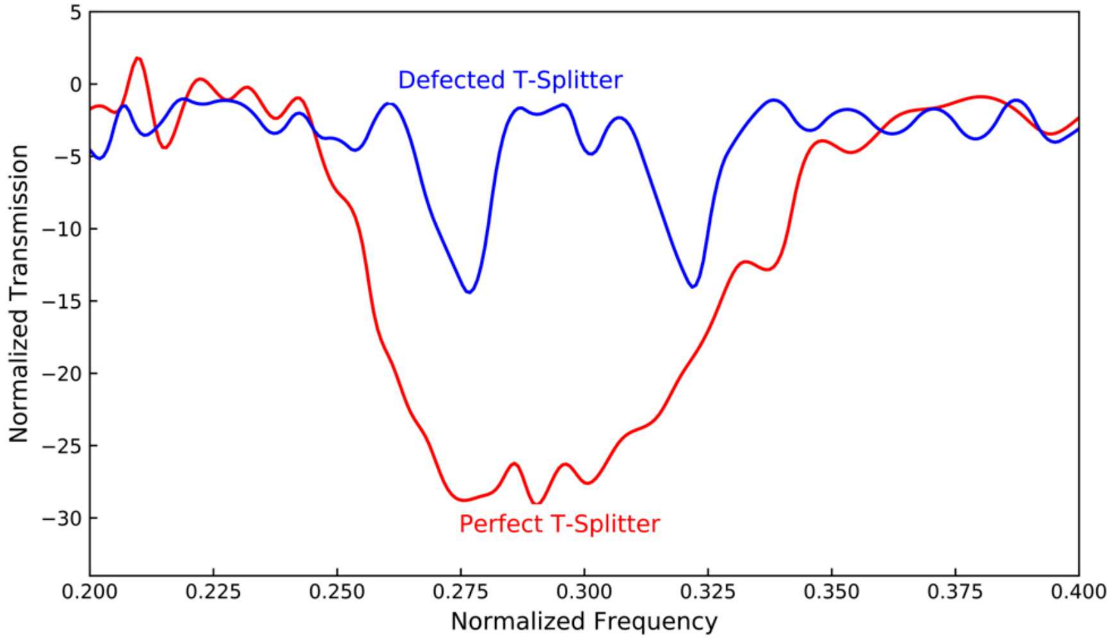
- A "T" splitter waveguide was designed and fabricated with $\alpha = 0.1$
  - Splitting angle is 180°
- As with the bent waveguide, the lattice was slightly perturbed in the bend region by the introduction of reduced-size holes
- Waves are excited at the bottom of the device and measured at either of the two output arms

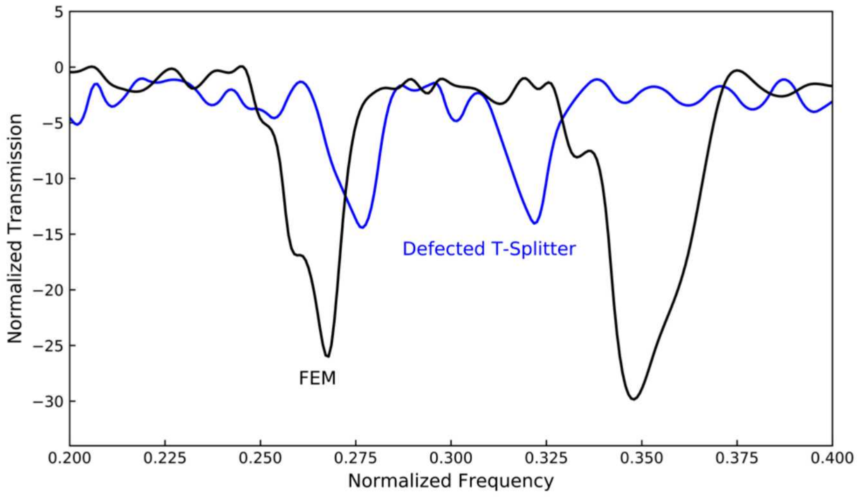




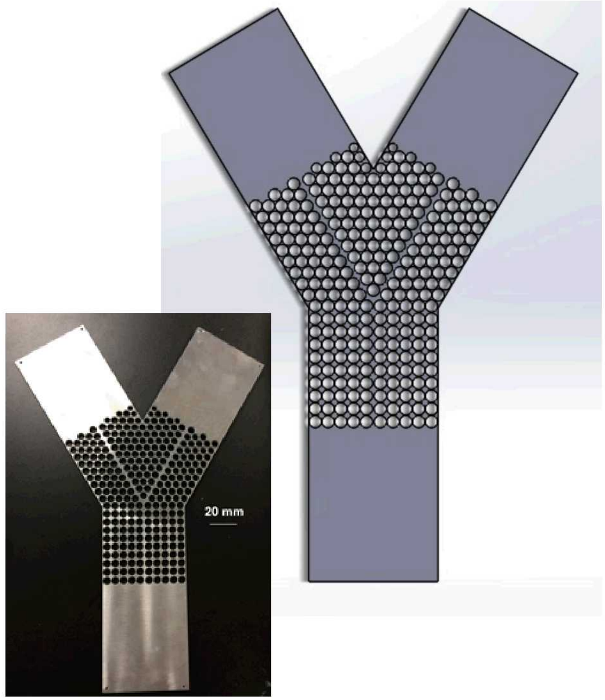
PnC T-Splitter Design

- The splitter shows a passband from 0.28-0.3 in normalized frequency
  - The average transmission is about -3.4dB, which corresponds to 80% energy transmission
- FEM results are in a good agreement with experimental measurement
  - FEM results shows a deeper and wider bandgap, similar to the perfect PnC
  - The bandgap moved slightly due to the change in the PnC lattice

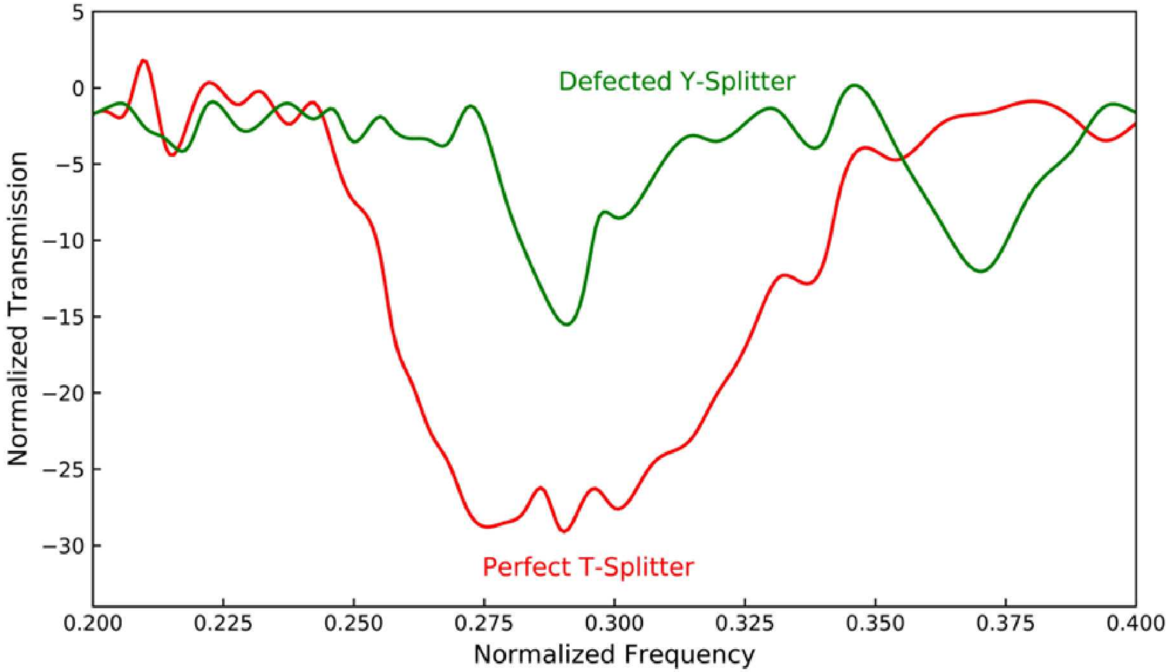


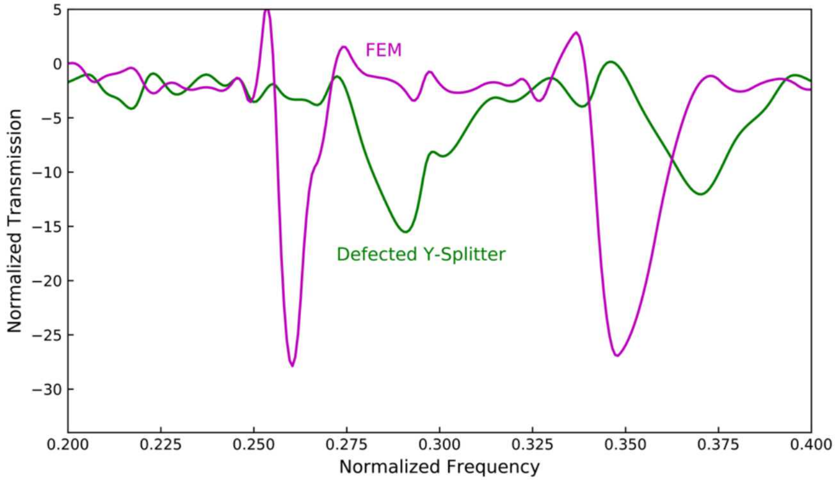


PnC Y-Splitter Design



- A "Y" splitter waveguide was also designed and fabricated with α = 0.1
- Lattice is changed from cubic to hexagonal in the splitting region
  - Splitting angle is 30°
- Measured average transmission is about -2.86dB, which corresponds to 72% energy transmission





Conclusions

- Well-confined waveguiding can be realized by mode engineering in PnCs
- Transmission as high as 90% in the bent waveguide was demonstrated
- Efficient power splitting was demonstrated in both “T” (180°) and “Y” (30°) splitters
- These designs offers a paradigm based on bulk acoustic waves (BAW) for the design of next generation RF signal processing devices filters

Demonstration of Waveguiding, Bends, Splitters in Macro-Scale Phononic Crystal Devices

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