# 7/14

LiNbO3 phononic crystal (PnC) first band structure attempt

# Intro: LiNbO3, SAW, microfabrication

Lithium niobate (LiNbO3)

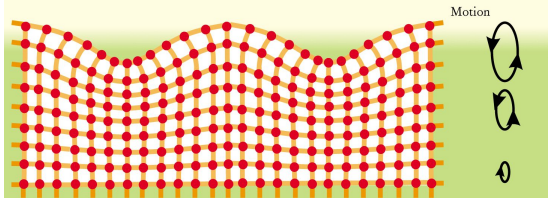
- Used extensively in telecom for optical modulators & acousto-optic devices
- Also large piezoelectric coupling

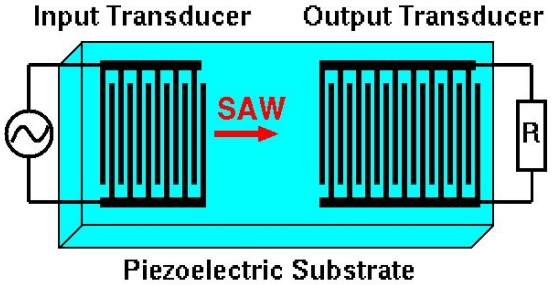
Surface acoustic waves (SAW)

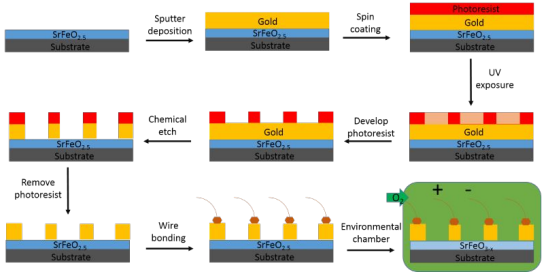
- Elastic waves confined to the surface of a material, decaying by depth of ~1λ
- In piezoelectric materials like LiNbO3: excited using interdigital transducers (IDT's)

Microfabrication ("fab")

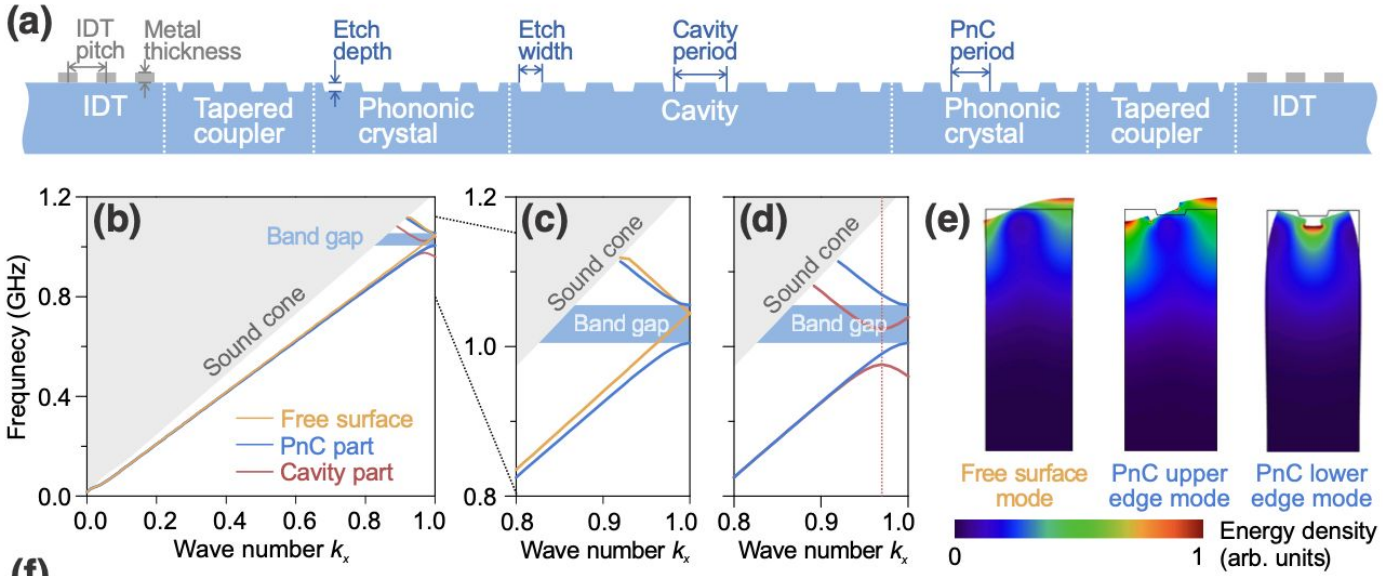
- Techniques to etch away or deposit material in microscale patterns
- Basis for semiconductor devices, MEMS, etc.



# Literature (Shao et al.): LiNbO3 phononic crystal (PnC)




Objective: Start LiNbO3 SAW fab & simulation with a simple 1D structure

(a) Linbo Shao's 1D resonator design
(b)-(d) Blue lines and bandgap are for PnC

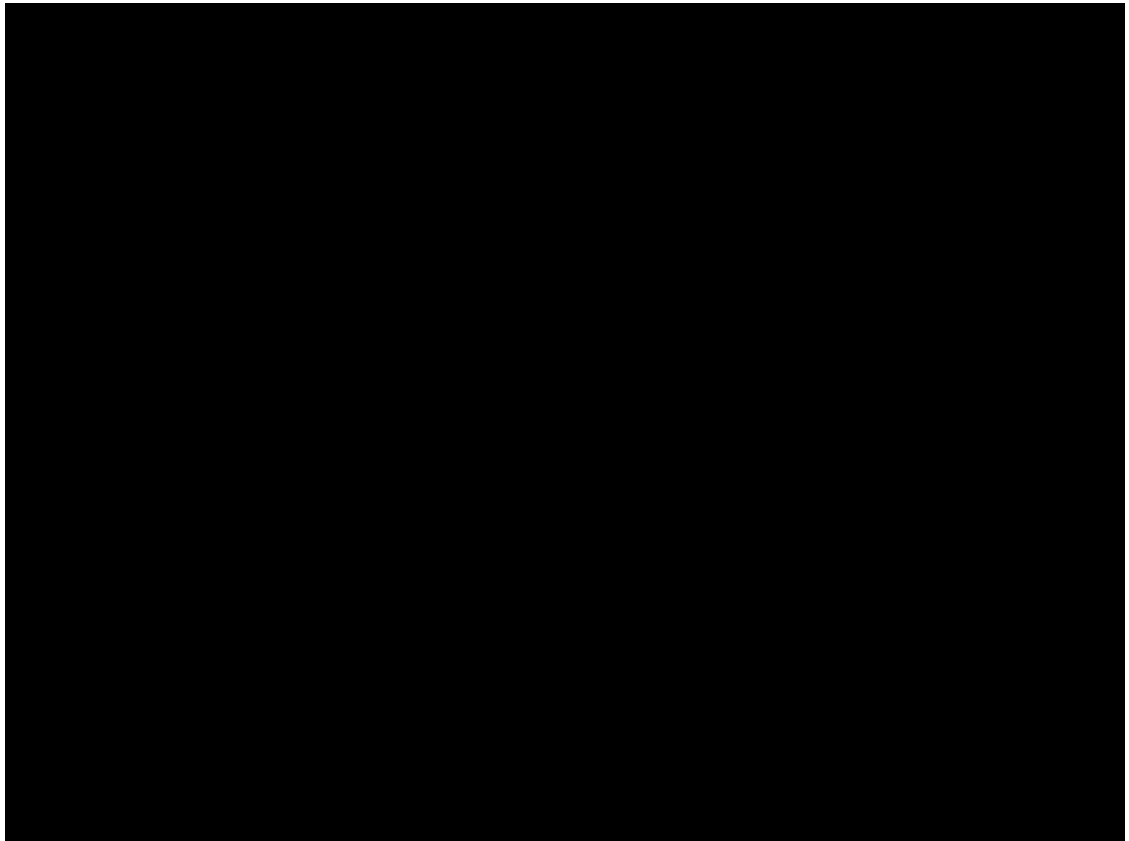
- Having periodic grooves creates bandgap
- Bottom line is s mode, top is p mode

(e) Unit cell mode shapes

First steps:

- Simulation (SAW's: fix bottom boundary)
- Ideal PnC (infinite system/BC's, constant period)
- 2 bands in (d): s mode (bottom), then p mode (top)

# S mode shape for K-point (k=pi/W): good



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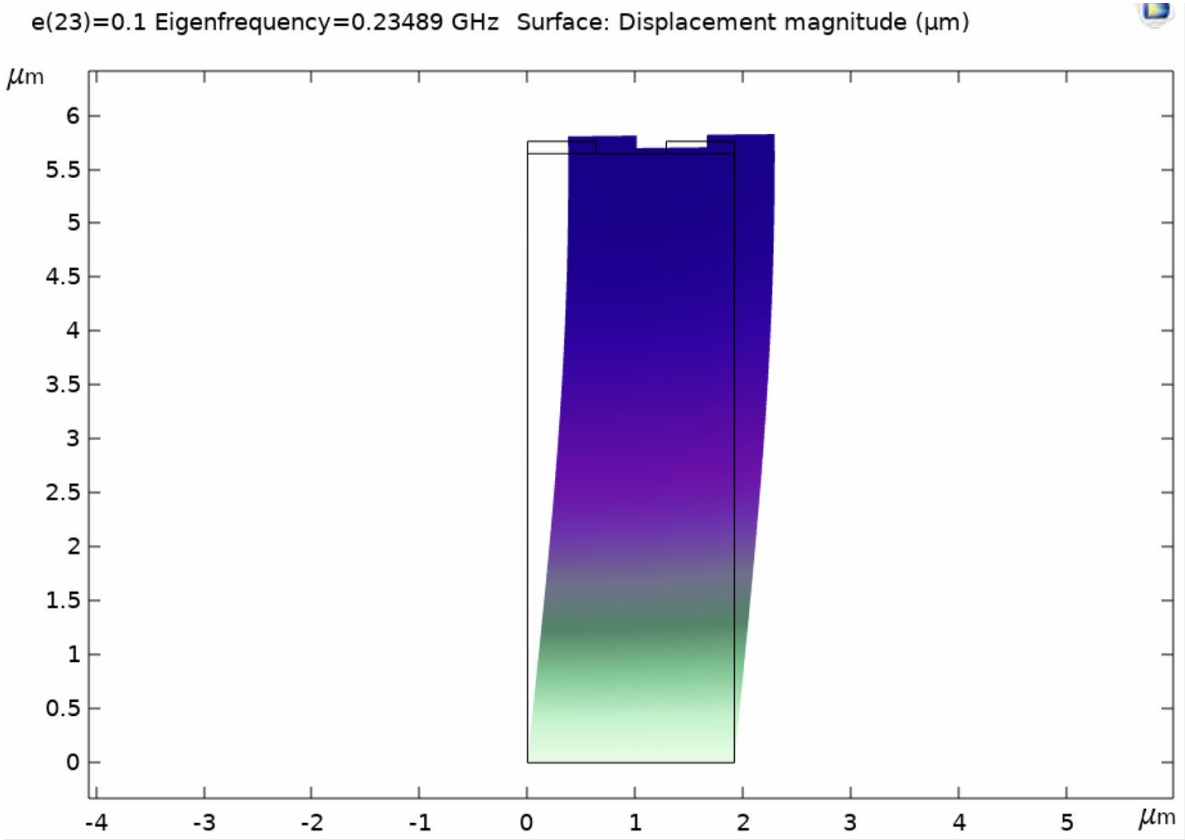
# S mode shape for small k: bad, SAW not constrained to surface

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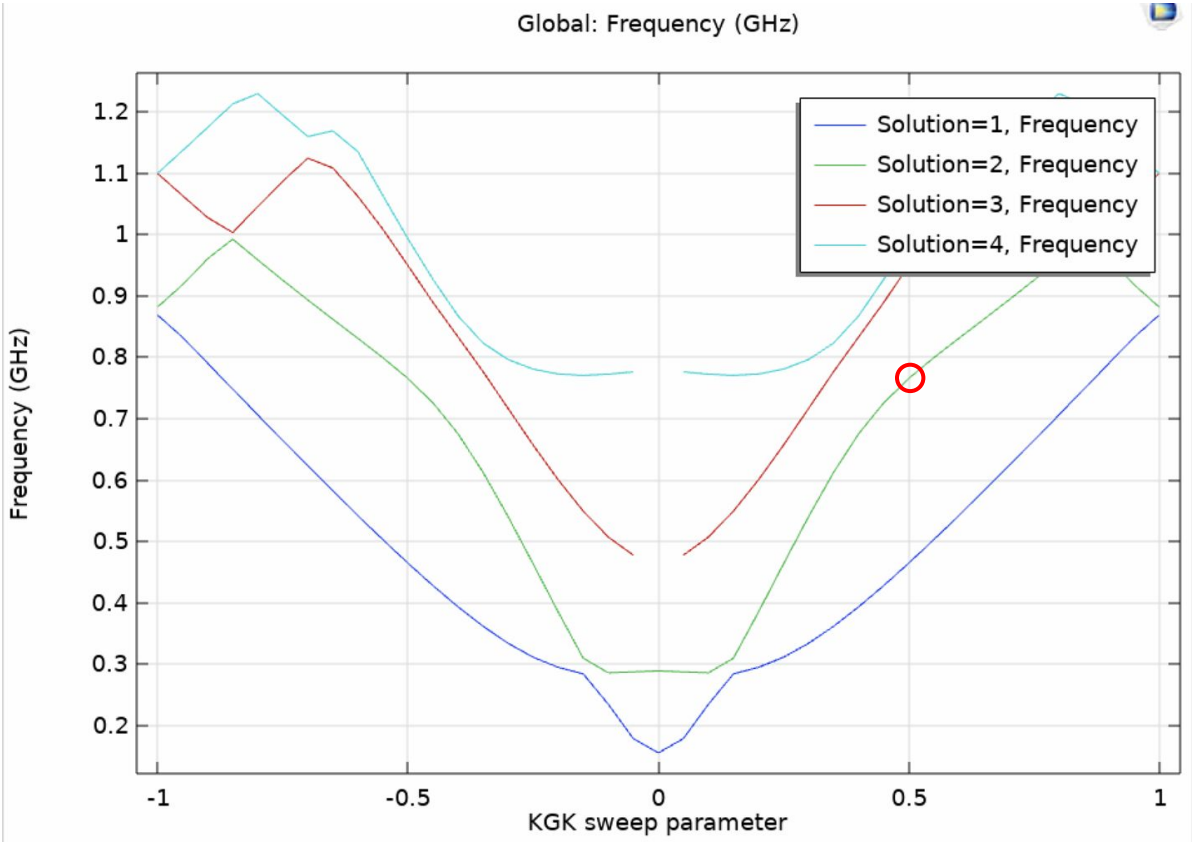
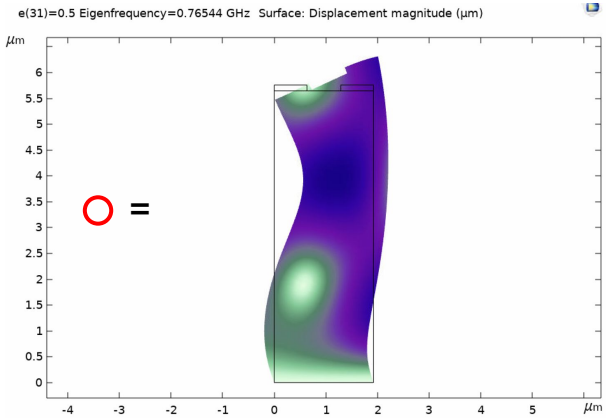
# S band structure (bottom blue band)




- Bottom blue s band has a divet near k=0 due to failed SAW constraint (material not deep/elastic enough)
- Solution: Increase material depth from L=3*W to 30*W
- Extraneous bands above:




[except green band for large |k| (near pi/L)]

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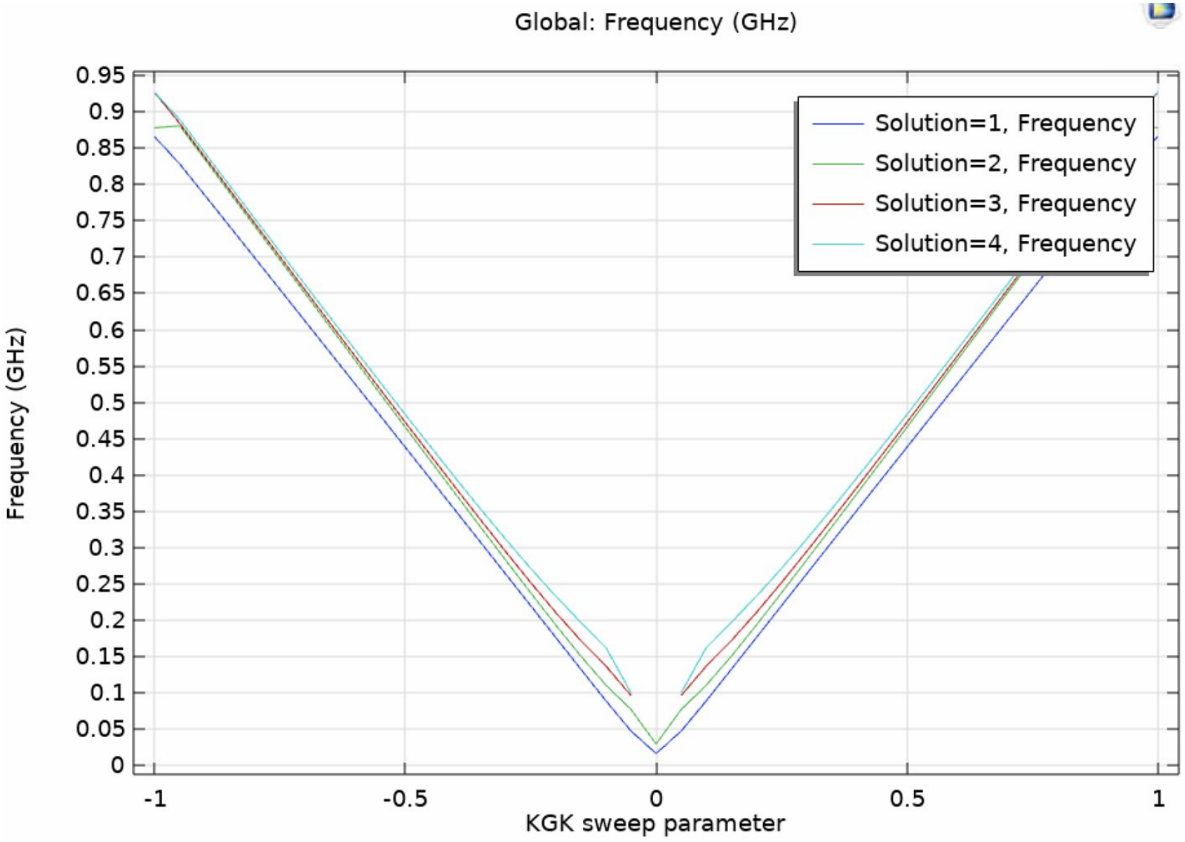
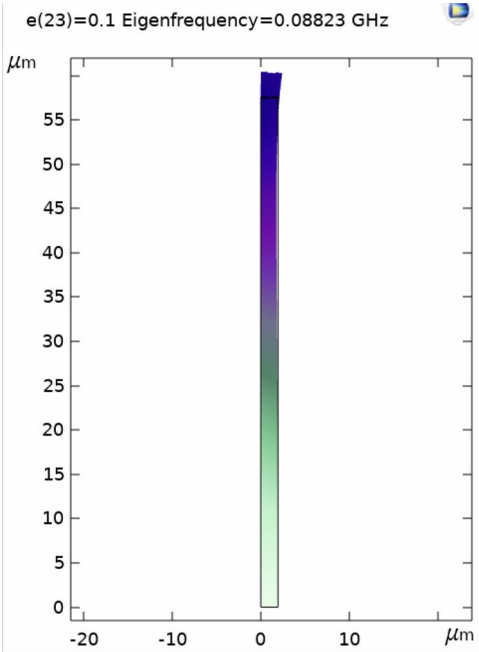
# S band structure (bottom blue) with L=30*W




Bottom blue s band no longer has divet near k=0; better constraining at surface

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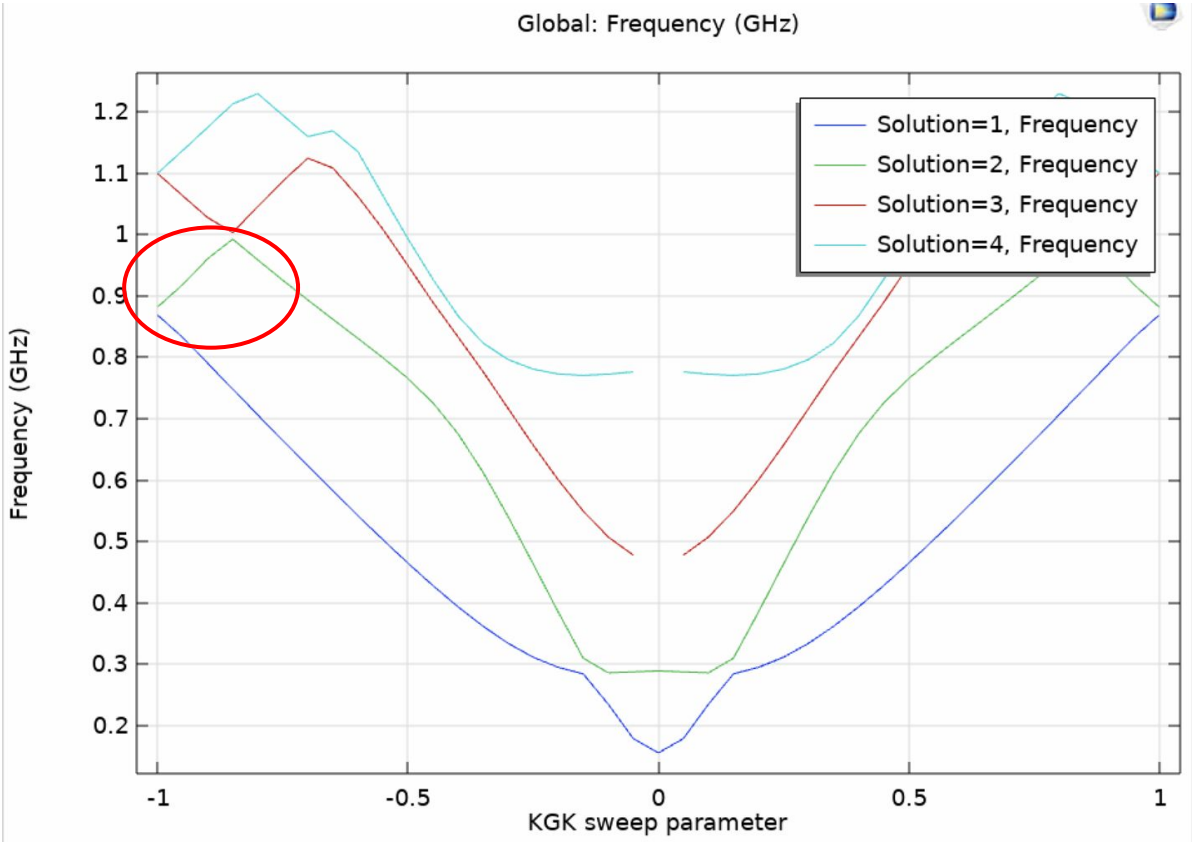
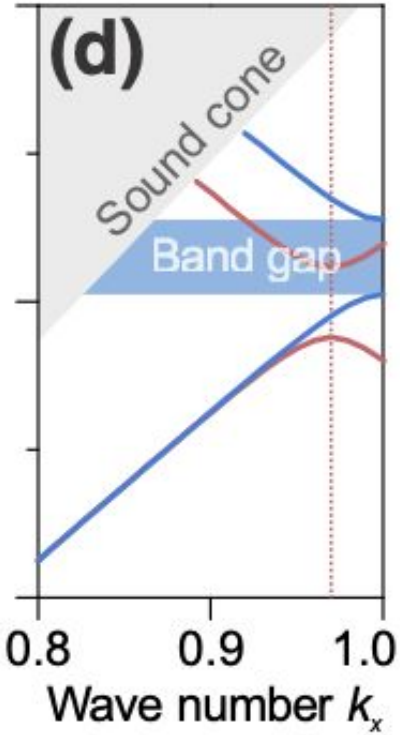
# P band structure (green) with L=3*W, for |k| near pi/W




Compare to:

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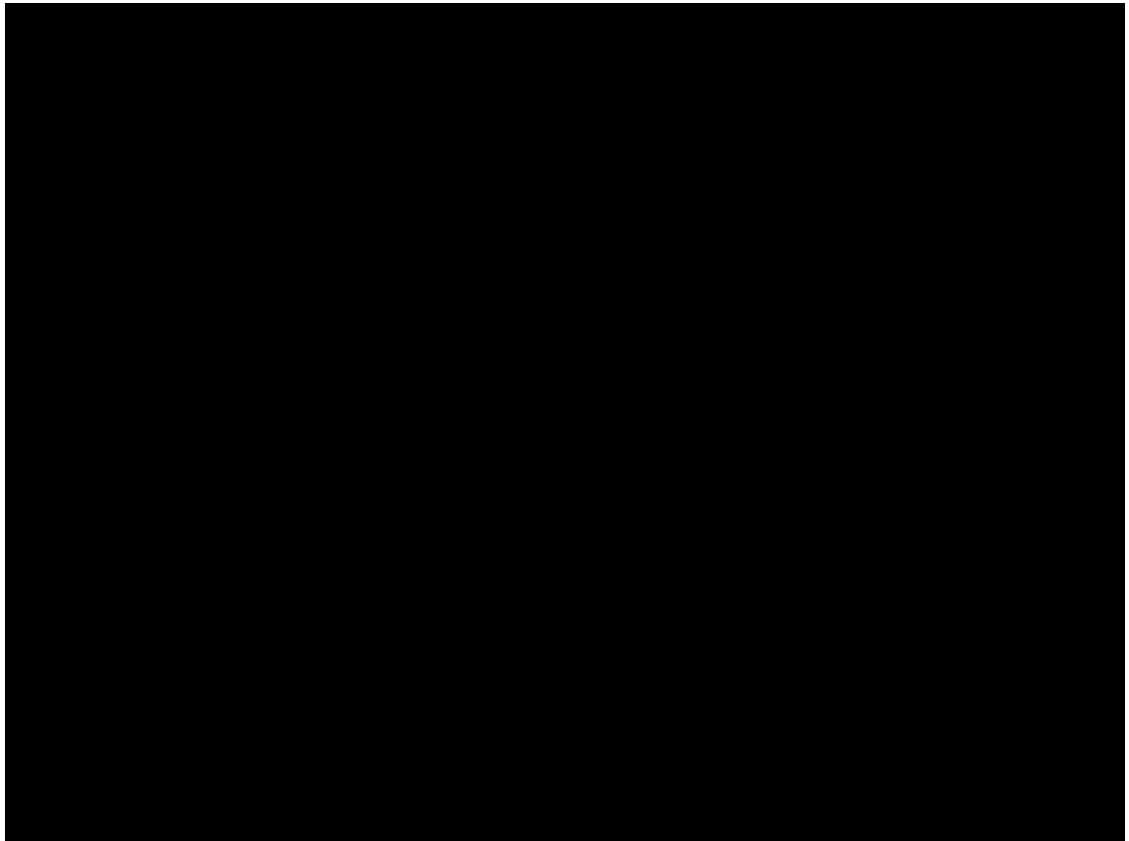
# P mode for K-point (k=pi/W): good



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# Discussion/questions

- Is this the band structure that I wanted to replicate from Linbo's paper? The eigenfrequencies don't exactly match, but I didn't put in the exact 128YX-cut LiNbO3 parameters (I used YZ-cut parameters). Is it qualitatively correct?
- Next steps
  - Chat with Sophie about this simulation
  - Change to finite case (no infinite Floquet periodicity)
  - Simulate cavity (by having monotonic period sequence rather than constant)
  - Simulate whole thing together (with tapered coupler?)
  - In parallel: fab with David, kind of waiting on his reply but he replies within a couple days

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# 7/19

LiNbO3 phononic crystal (PnC) updates: simulation, fab

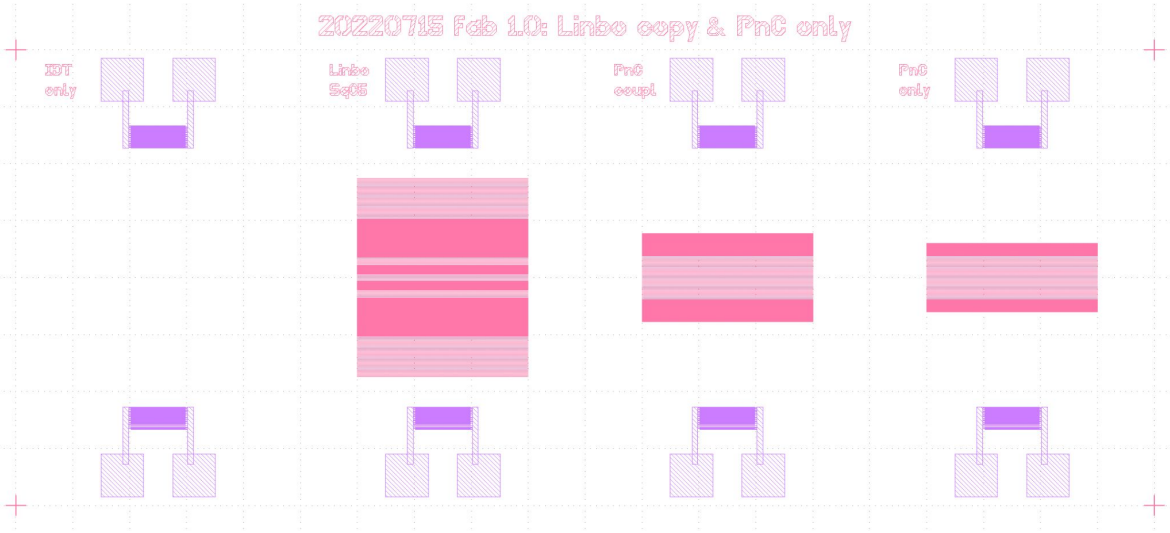
# First fab

Design consists of:

1. IDT’s only, no etch
2. IDT’s + “SqC5” etch from Linbo (entire SAW resonator from his paper: with tapered couplers, PnC’s, cavity)
3. IDT’s + PnC (63 grooves) + 2 tapered couplers (9 grooves each)
4. IDT’s + PnC only (63 grooves)

Pink: etch

Purple: metal deposition




IDT’s only

IDT’s + Resonator from Linbo paper (tapered couplers, PnC’s, cavity)

IDT’s + PnC + tapered couplers (no cavity)

IDT’s + PnC only

# Next steps

- Fab, testing, analysis
- Read more literature on SAW devices/resonators to see how we can design etched phononic graphene
    - What are our resonators and hopping couplers?

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# 7/26

LN 1D PnC design & fab updates

Pillar-plate phononic graphene discussion, acoustic tight-binding dispersion $\omega^2$ vs. k

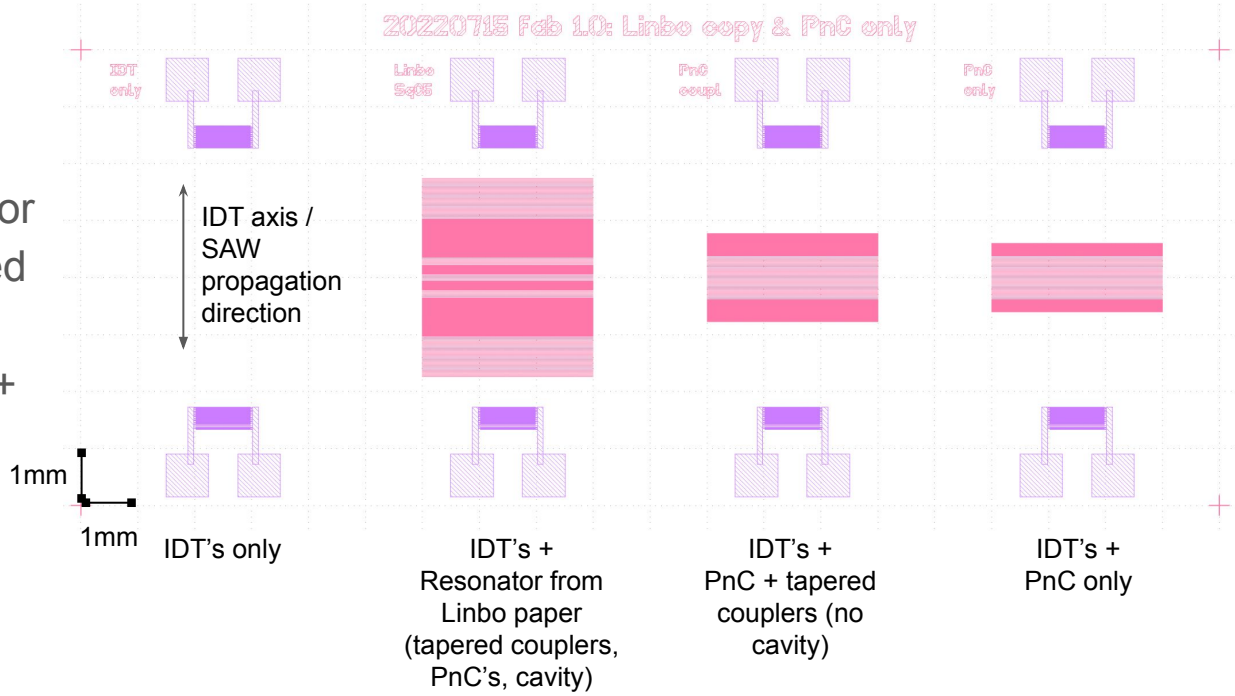
# Recall: 1D PnC Fab

Pink: etch

Purple: metal deposition

Design set:

1. IDT's only, no etch
2. IDT's + "SqC5" etch from Linbo (entire SAW resonator from his paper: with tapered couplers, PnC's, cavity)
3. IDT's + PnC (63 grooves) + 2 tapered couplers (9 grooves each)
4. IDT's + PnC only (63 grooves)

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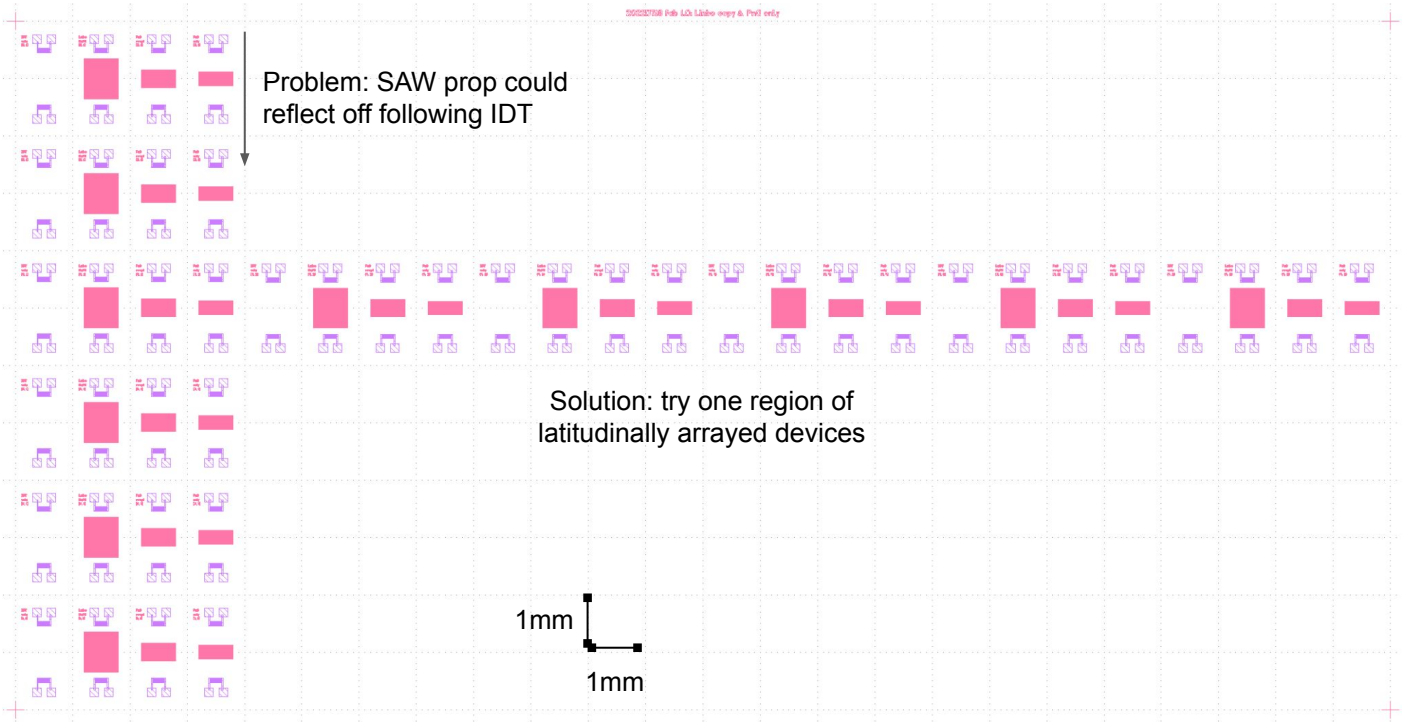
# 1D PnC Array Fab




Due to possible concerns about SAW reflection from further IDT's, create array with one column and one row

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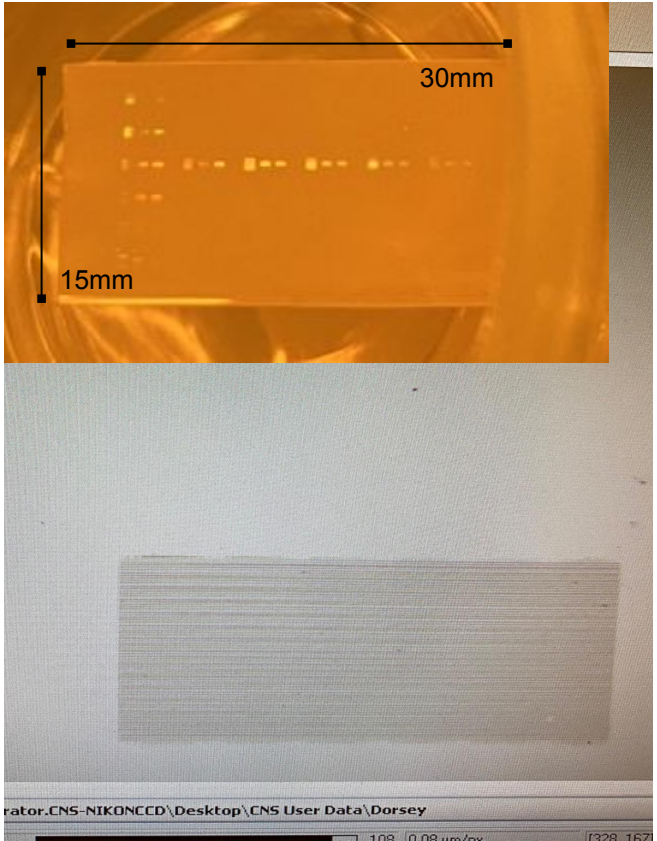
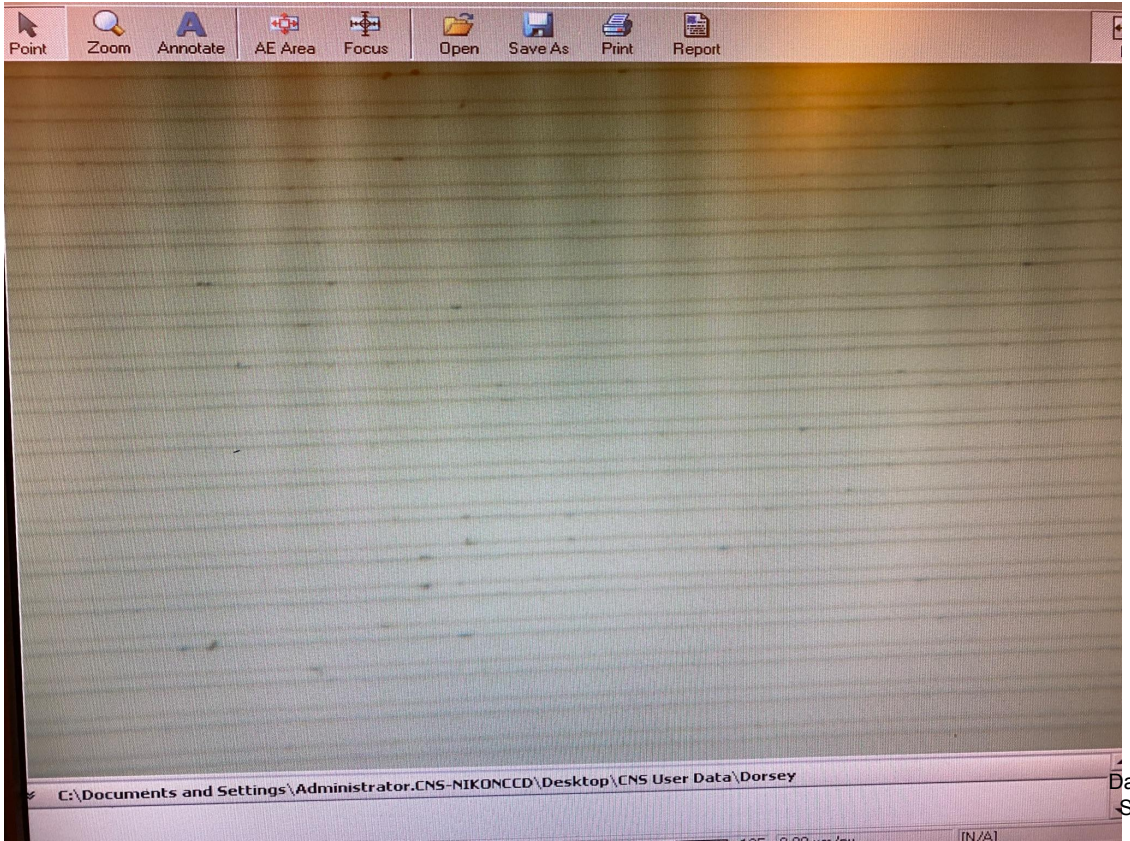
# Photolithography & etch

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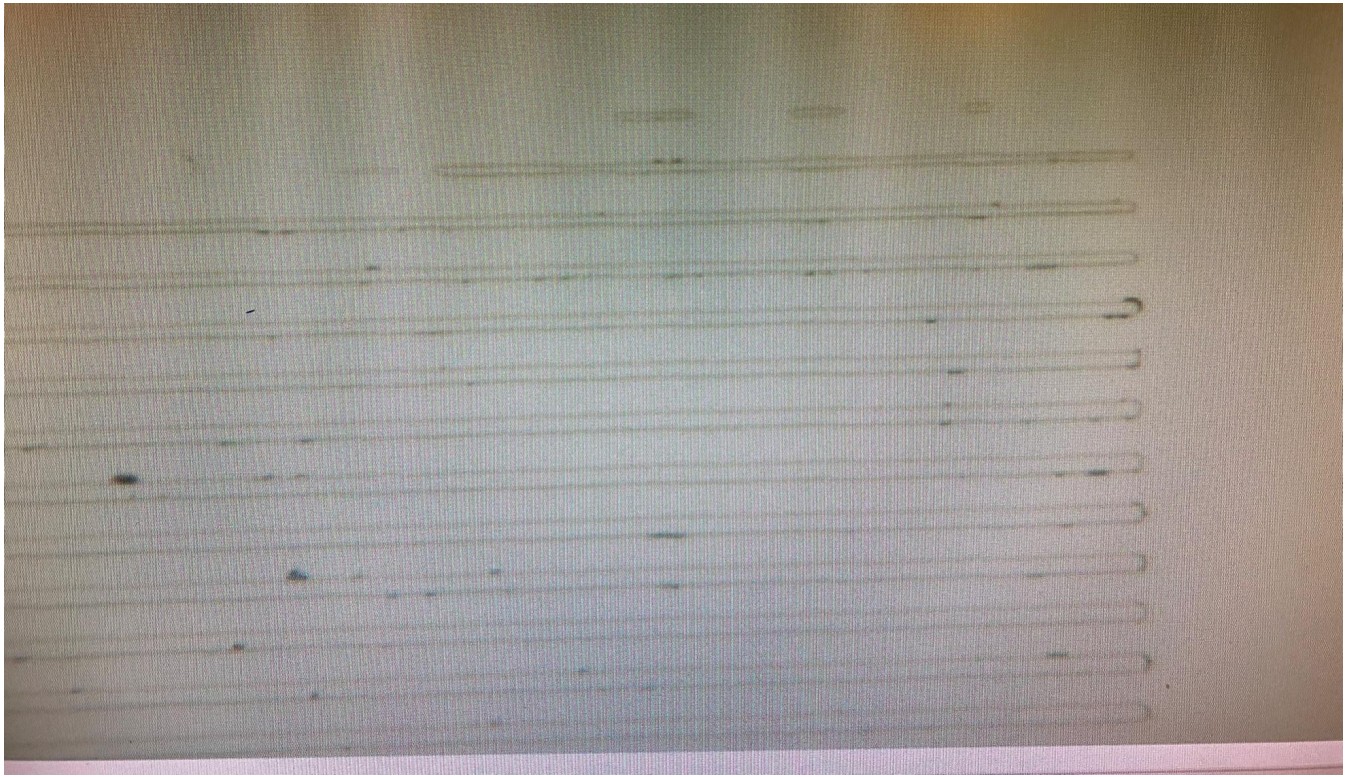
# Photolithography & etch



- Tapered coupler not fully etched due to resolution limits
- Remaining resist gunk despite doing strong- cleaning “piranha” process
- Move on

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# Quantum Tight-Binding Model

Single particle Hamiltonian of lattice $\hat{H}$, single atom Hamiltonian $\hat{H}_{at}$:

$$\hat{H} = \hat{H}_{at} + \Delta\hat{U} \tag{21}$$

Atomic wavefunction eigenstates $\phi_i(r)$ of $\hat{H}_{at}$:

$$\hat{H}_{at}\phi(r) = \epsilon\phi(r) \tag{22}$$

Single particle eigenstates $\psi_{\mathbf{k}}(r)$:

$$\hat{H}\psi_{\mathbf{k}}(r) = E_{\mathbf{k}}\psi_{\mathbf{k}}(r) \tag{23}$$

Single particle eigenstates obey Bloch's theorem:

$$\psi_{\mathbf{k}}(\mathbf{r}+\mathbf{R}) = e^{i\mathbf{k}\cdot\mathbf{R}}\psi_{\mathbf{k}}(\mathbf{r}) \tag{24}$$

Bloch-satisfying LCAO:

$$\psi_{\mathbf{k}}(\mathbf{r}) = \frac{1}{\sqrt{N}}\sum_{\mathbf{R}} e^{i\mathbf{k}\cdot\mathbf{R}}\phi(\mathbf{r}-\mathbf{R}) \tag{25}$$

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# Quantum Tight-Binding Band Structure

Hence, band structure of energy $E$ vs. wavevector $\mathbf{k}$:

$$E(\mathbf{k}) = \int \psi_{\mathbf{k}}^*(\mathbf{r})\hat{H}\psi_{\mathbf{k}}(\mathbf{r})d\mathbf{r} \tag{26}$$

$$= \frac{1}{N}\sum_{\mathbf{R}}\sum_{\mathbf{R}'} e^{i\mathbf{k}\cdot(\mathbf{R}'-\mathbf{R})} \int \phi^*(\mathbf{r}-\mathbf{R})\hat{H}\phi(\mathbf{r}-\mathbf{R}')d\mathbf{r} \tag{27}$$

$$= \cdots \tag{28}$$

$$= \sum_{\mathbf{R}''} e^{i\mathbf{k}\cdot\mathbf{R}''} \int \phi^*(\mathbf{x})\hat{H}\phi(\mathbf{x}-\mathbf{R}'')d\mathbf{x} \tag{29}$$

where $\mathbf{R}, \mathbf{R}', \mathbf{R}''$ range over all lattice sites

Assuming only nearest-neighbor $\boldsymbol{\tau}$ hopping, we then have the band structure

$$E(\mathbf{k}) = \sum_{\boldsymbol{\tau}} e^{i\mathbf{k}\cdot\boldsymbol{\tau}}\gamma(\boldsymbol{\tau}) \tag{30}$$

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# Acoustic Tight-Binding Model: General

General acoustic standing wave equation

$$\hat{J}W(\mathbf{r}) = \omega^2 W(\mathbf{r}),$$

where $W(\mathbf{r})$ is the (complex) amplitude of some wave quantity such as displacement or pressure, and $\hat{J}$ is shorthand for some expression operating on $W(\mathbf{r})$.

$\omega^2$ arises from the fact that acoustic wave equations use the second time derivative, as opposed to the first time derivative in the Schrödinger equation.

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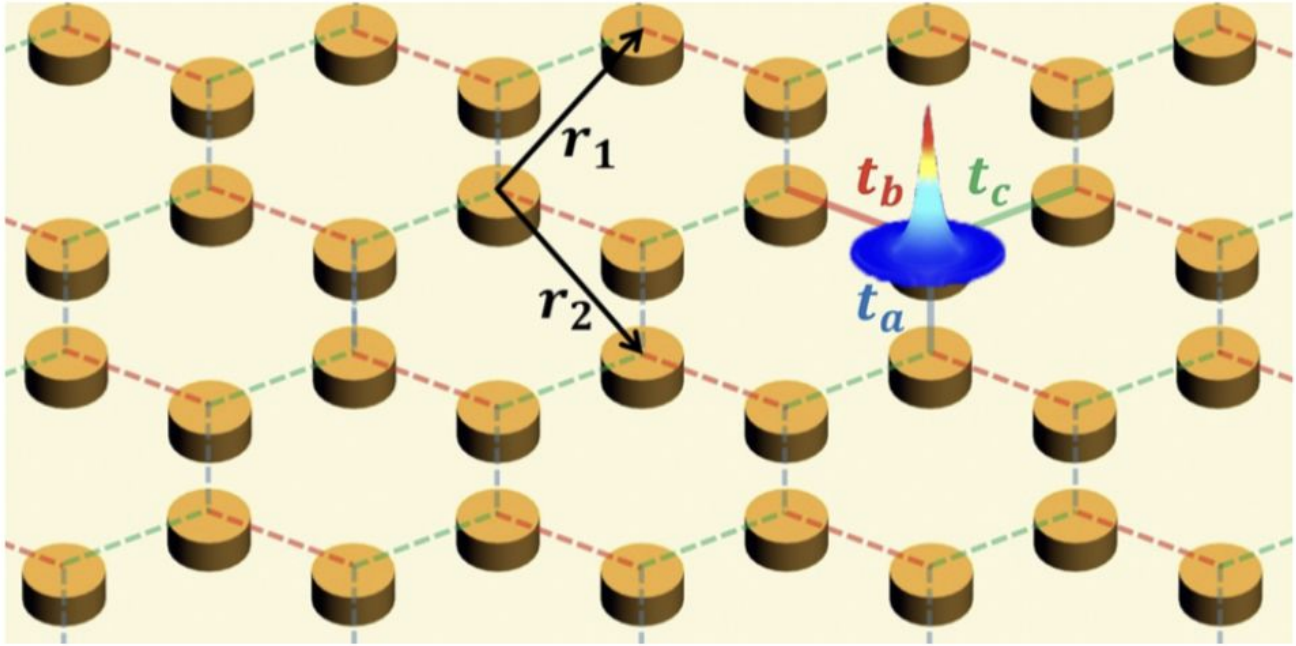
# Acoustic Tight-Binding Model: Ex. Pillar-Plate Graphene

Nickel micro-pillars in a honeycomb pattern on a thin-plate LiNbO3 substrate (Yu et al. 2016):

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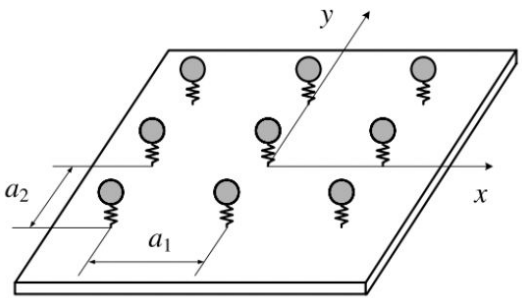
# Acoustic Tight-Binding Model: Ex. Pillar-Plate Graphene

For modeling purposes, each pillar resonator modeled as a mass-spring connected to the substrate (Xiao et al. 2012):




Resulting standing wave equation for transverse amplitude $W(\mathbf{r})$:

$$\hat{J}W(\mathbf{r}) = \frac{D}{\rho h}\left(\nabla^4 - \sum_{\mathbf{R}_n}\sum_{\alpha=1}^{2}\tau\delta(\mathbf{r}-\mathbf{R}_{n\alpha})\right)W(\mathbf{r}) = \omega^2 W(\mathbf{r}). \tag{31}$$

- $\nabla^4$: wave equation in thin plate free space
- Sum over delta functions: effect of spring-mass systems

$\hat{J}$ isn't energy, but it has a similar effect as the quantum Hamiltonian in producing tight-binding eigenvalues. (If you'd like, you can call it a sort of faux acoustic "Hamiltonian.")

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# Acoustic Tight-Binding Model

Next, in analogy to localized atomic wavefunctions in the quantum case, consider an isolated resonator of the acoustic system of interest. Wave equation:

$$\hat{J}_0 W_0(\mathbf{r}) = \omega_0^2 W_0(\mathbf{r}). \tag{32}$$

Ex. pillar-plate graphene — single pillar and some nearby LiNbO3 substrate:

The localized wave equation only includes the effect of one pillar:

$$\hat{J}_0 W_0(\mathbf{r}) = \frac{D}{\rho h}\left(\nabla^4 - \tau\delta(\mathbf{r} - \mathbf{R}_{01})\right) W_0(\mathbf{r}) = \omega_0^2 W_0(\mathbf{r}).$$

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# Acoustic Tight-Binding Model

Make same assumption as in quantum tight-binding model: Bloch-satisfying linear combination of localized waves

$$W(\mathbf{r}) = \frac{1}{\sqrt{N}} \sum_{\mathbf{R}_n} \sum_{\alpha=1}^{2} e^{i\mathbf{k}\cdot\mathbf{R}_{n\alpha}} W_0(\mathbf{r} - \mathbf{R}_{n\alpha}). \tag{34}$$

- Translational invariance justifies equal weights in the linear combination
- Unsure how to justify acoustic equivalent of Bloch theorem?

Then as long as $\hat{J}$ is an additive operator, assuming 0 neighbor overlap integrals,

$$\int W^*(\mathbf{r})\hat{J}W(\mathbf{r})d\mathbf{r} = \omega^2 \int W^*(\mathbf{r})W(\mathbf{r})d\mathbf{r} \tag{35}$$

$$\sum_{\mathbf{R}}\sum_{\mathbf{R}'} e^{i\mathbf{k}\cdot(\mathbf{R}'-\mathbf{R})} \int W_0^*(\mathbf{r}-\mathbf{R})\hat{J}W_0(\mathbf{r}-\mathbf{R}')d\mathbf{r} = \omega^2 \sum_{\mathbf{R}}\sum_{\mathbf{R}'} e^{i\mathbf{k}\cdot(\mathbf{R}'-\mathbf{R})} \int W_0^*(\mathbf{r}-\mathbf{R})W_0(\mathbf{r}-\mathbf{R}')d\mathbf{r} \tag{36}$$

$$\sum_{\mathbf{R}''} e^{i\mathbf{k}\cdot\mathbf{R}''} \int W_0^*(\mathbf{x})\hat{J}W_0(\mathbf{x}-\mathbf{R}'')d\mathbf{x} = \omega^2 \sum_{\mathbf{R}''} e^{i\mathbf{k}\cdot\mathbf{R}''} \int W_0^*(\mathbf{x})W_0(\mathbf{x}-\mathbf{R}'')d\mathbf{x} \tag{37}$$

$$= \omega^2 \int W_0^*(\mathbf{x})W_0(\mathbf{x})d\mathbf{x}. \tag{38}$$

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# Acoustic Tight-Binding Band Structure

Further again assuming only nearest-neighbor $\boldsymbol{\tau}$ hopping, we have the following acoustic tight-binding dispersion relation between $\omega$ and $\mathbf{k}$:

$$\omega^2 = \sum_{\boldsymbol{\tau}} e^{i\mathbf{k}\cdot\boldsymbol{\tau}} \left( \frac{\int W_0^*(\mathbf{x}) \hat{\int} W_0(\mathbf{x}-\boldsymbol{\tau}) d\mathbf{x}}{\int W_0^*(\mathbf{x}) W_0(\mathbf{x}) d\mathbf{x}} \right) \tag{19}$$

$$= \sum_{\boldsymbol{\tau}} e^{i\mathbf{k}\cdot\boldsymbol{\tau}} \gamma'(\boldsymbol{\tau}). \tag{20}$$

Thus note the correspondence between quantum:

$$E(\mathbf{k}) = \sum_{\boldsymbol{\tau}} e^{i\mathbf{k}\cdot\boldsymbol{\tau}} \gamma(\boldsymbol{\tau}) \tag{30}$$

and acoustic:

$$\omega^2 = \sum_{\boldsymbol{\tau}} e^{i\mathbf{k}\cdot\boldsymbol{\tau}} \gamma'(\boldsymbol{\tau}). \tag{40}$$

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# Acoustic Tight-Binding: Summary & Discussion

- Crucial assumptions for any acoustic tight-binding metamaterial:
  - $\omega^2$ eigenvalue in wave equation: $\hat{J}W(\mathbf{r}) = \omega^2 W(\mathbf{r}),$
  - Bloch-satisfying linear combination of localized waves:

$$W(\mathbf{r}) = \frac{1}{\sqrt{N}} \sum_{\mathbf{R}_n} \sum_{\alpha=1}^{2} e^{i\mathbf{k}\cdot\mathbf{R}_{n\alpha}} W_0(\mathbf{r} - \mathbf{R}_{n\alpha}).$$

- Once we have these assumptions, some manipulation quickly yields

$$\omega^2 = \sum_{\boldsymbol{\tau}} e^{i\mathbf{k}\cdot\boldsymbol{\tau}} \gamma'(\boldsymbol{\tau}).$$

- However, *if there is some eigenfunction in the acoustic system with eigenvalue $\omega$, and we assume it satisfies a Bloch linear combination of localized waves*, then we would actually have

$$\omega = \sum_{\boldsymbol{\tau}} e^{i\mathbf{k}\cdot\boldsymbol{\tau}} \gamma'(\boldsymbol{\tau}).$$

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# 8/9

Dose testing update

# Dose testing

Photolithography = Exposing resist with light to change its chemical properties, making it more/less soluble (which will be dissolved in solution) as to create a “mask” for etching, deposition, etc. later

Dose testing = determining what energy intensity of light to use in photolithography

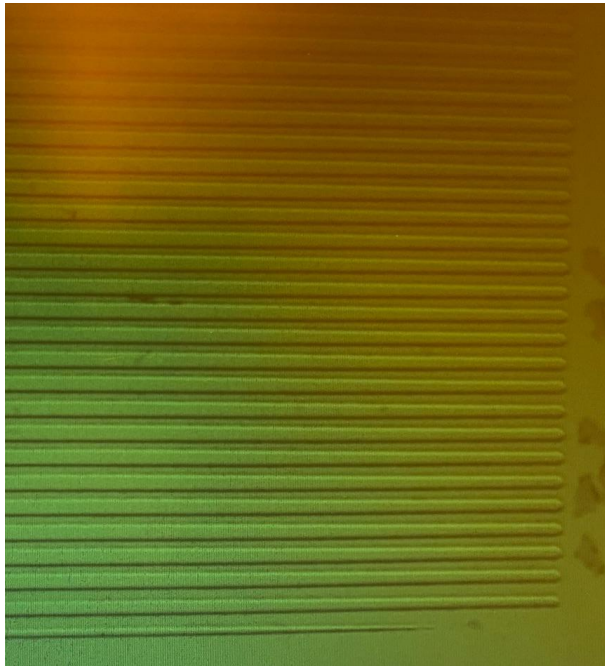
In practice: the photolithography machine produces an array of the inputted pattern with different doses (e.g., range 110-190 mJ/cm2)

# PnC dose testing

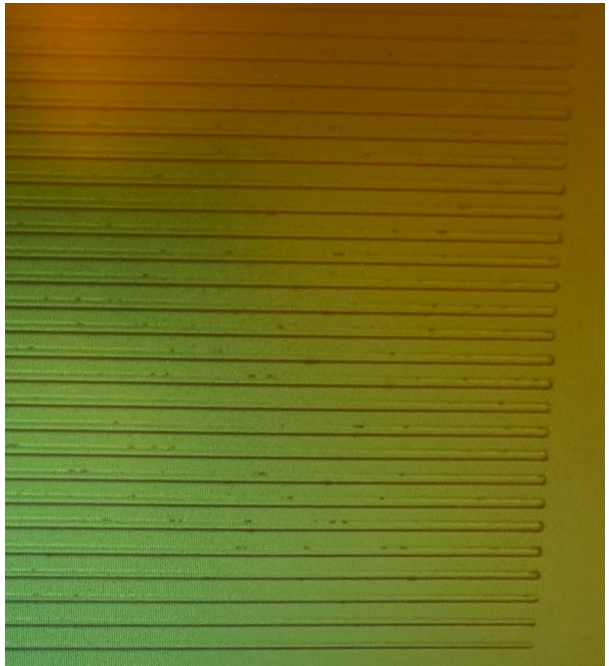
Etch width = 1.3um, period = 3.84um (approximately 1/3 proportion)

Underdosing: 110 mJ/cm2

Overdosing: 190 mJ/cm2



Good dosing: 125 mJ/cm2



# Summary & next steps

Dose testing

- Done with PnC dose testing, have yet to do deposition to finalize IDT dose testing
- Original suggested doses (from Loncar group process parameter precedents) seem to work

Next steps

- Try Linbo’s previous readout setup, start working with Gage & Sophie for transmission measurements
- Try to reproduce Linbo’s 1D PnC transmission graph that reflects PnC bandgap

# 9/2

Summer summary for whole group meeting

# Lithium niobate metamaterials

Lithium niobate (LiNbO3)

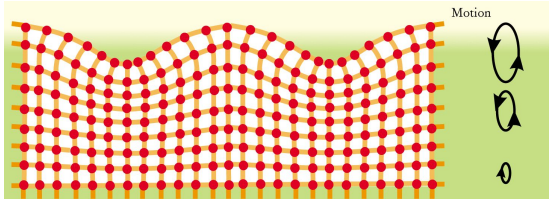
- Used in telecom for acoustic/optical modulators
- Large piezoelectric coupling

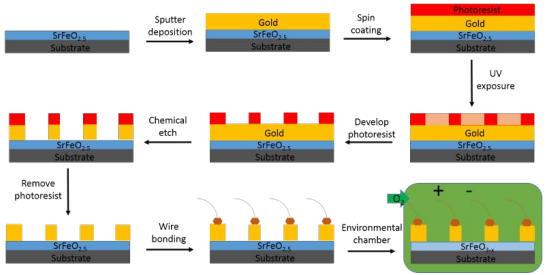
Surface acoustic waves (SAW)

- Confined to surface, depth of ~1λ

Microfabrication (“fab”)

- Techniques to etch away or deposit material in microscale patterns
- Basis for semiconductor devices, MEMS, etc.




***Objective:*** *Fab acoustic metamaterials of 1D chain, graphene, TBG in lithium niobate*

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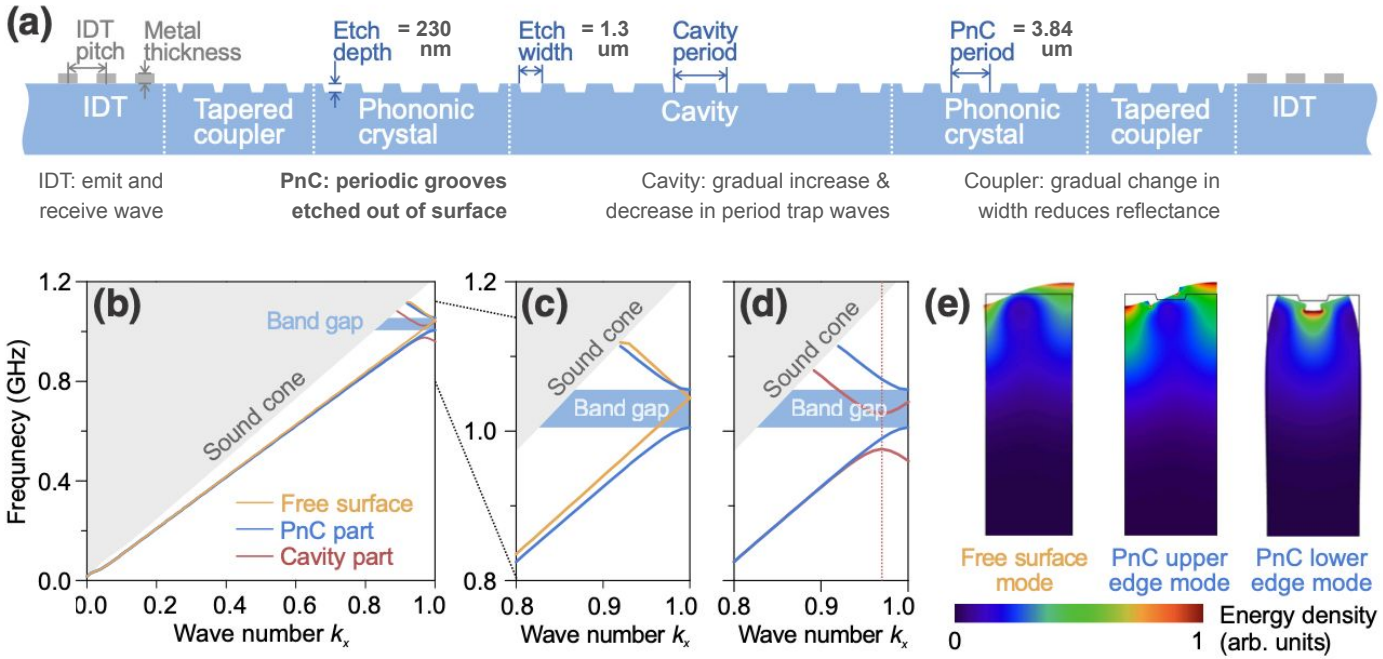
# First step: LiNbO3 1D chain (Shao et al., 2019)

*Replicate Shao et al.'s 1D chain "phononic crystal" in order to understand SAW and develop fabrication & testing techniques*




Key structure is the PnC, whose unit cell is shown in (e): a groove is etched away on the surface

These periodic grooves create a bandgap; the blue lines in (b)-(d) are the PnC's band structure

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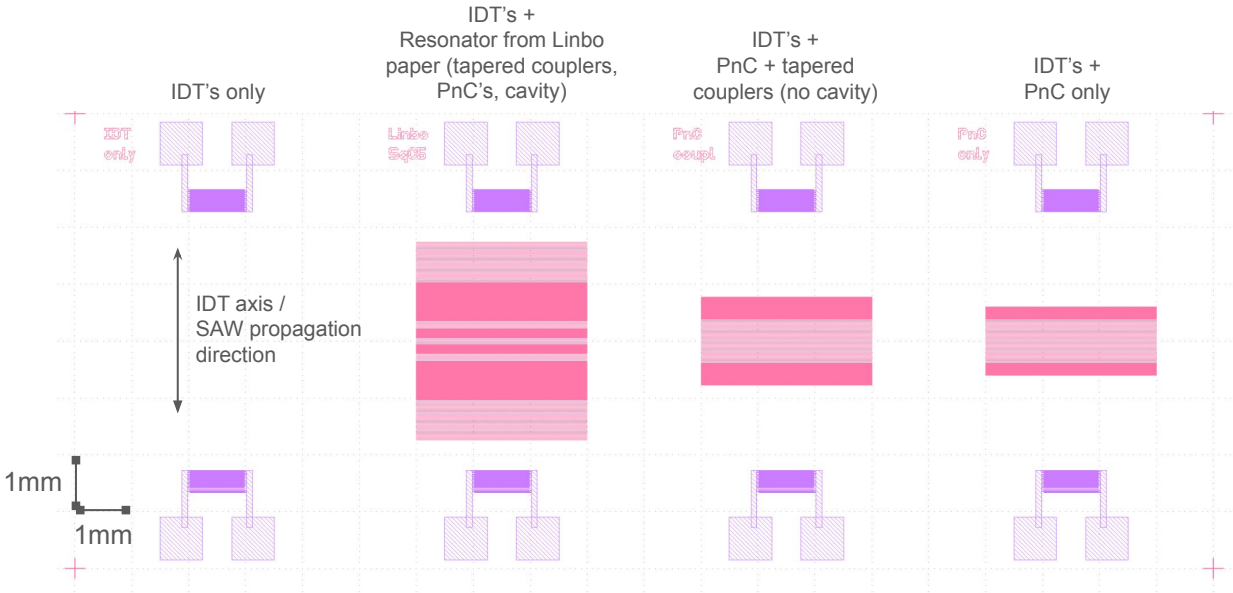
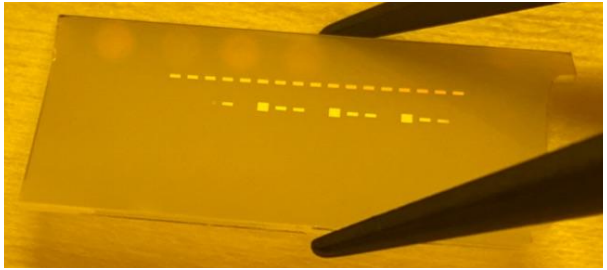
# Current progress: fabricating this 1D chain device

Periodic grooves have been etched for 3 chips, but each has been defective in some way (not fully etched, or cracked due to heat shock or tweezer tightness)

Design (pink: etch; purple: metal deposition):




E.g., one of the chips:



- 3 sets of designs were etched in the middle, but there should be an entire array of sets of designs
- The right edge is jagged because a small part broke off during heating
- This chip was turned into use for dose testing, on the top row

# Looking back, looking ahead

Techniques learned:

- Microfabrication processes (photolithography, etching, wet bench)
- Spec research (learning equipment, purchasing materials)
- Testing & analysis (dose testing, quantitative image analysis)
- Pattern design in Python, phidl, KLayout

Challenges:

- Experimental setbacks, e.g., unexpected failure to etch, chip cracking
- Resource delays

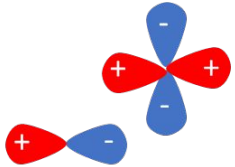
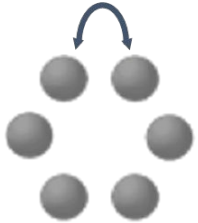
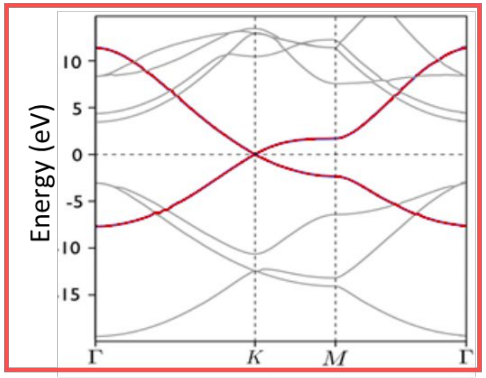
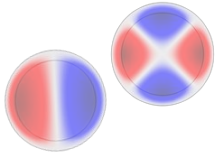
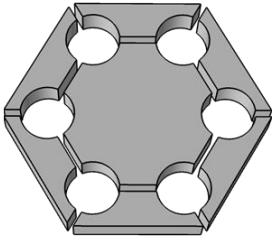
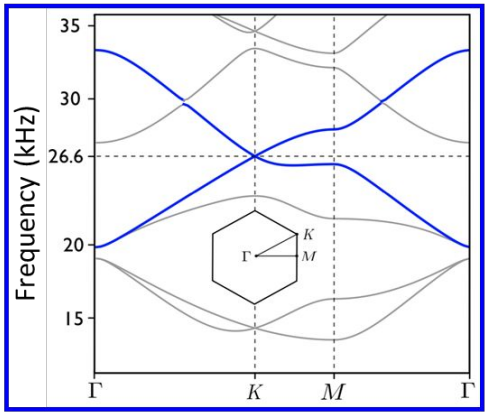
Next steps:

- Start new chip and hopefully don’t crack it (having learned from mistakes)
- Deposit metal for IDT’s for the first time

# 9/29

Lithium niobate metamaterial project overview/introduction for Federico

# Acoustic metamaterials simulate quantum materials

| | Wave Equations | Base States | Hopping | Band Structures |
|---|---|---|---|---|
| **Quantum Materials** | $\mathcal{H}\,\lvert\psi(\mathbf{r},t)\rangle = i\hbar\frac{\partial}{\partial t}\lvert\psi(\mathbf{r},t)\rangle$ Schrödinger Wave Equation |  Orbitals at Atomic Sites |  Tunneling Between Atomic Sites |  |
| **Acoustic Metamaterials** | $B(\mathbf{r})\left(\nabla\cdot\left[\frac{1}{\rho(\mathbf{r})}\nabla p(\mathbf{r})\right]\right) = \frac{\partial^2 p(\mathbf{r})}{\partial t^2}$ Acoustic Wave Equation |  Pressure Modes in Air Cavities |  Connecting Air Channels |  |

# Lithium niobate metamaterials

Lithium niobate (LiNbO3)

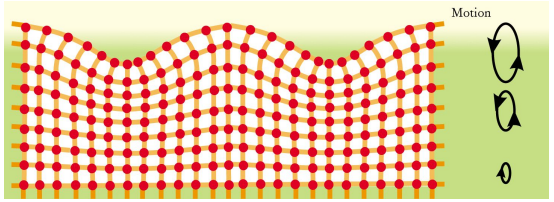
- Used in telecom for acoustic/optical modulators
- Large piezoelectric coupling

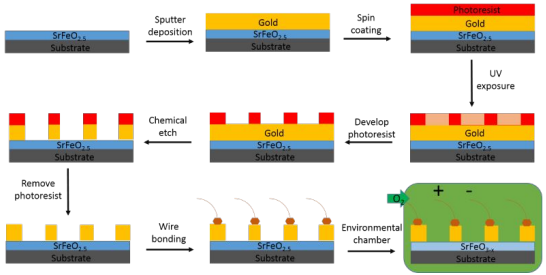
Surface acoustic waves (SAW)

- Confined to surface, depth of ~1λ

Microfabrication (“fab”)

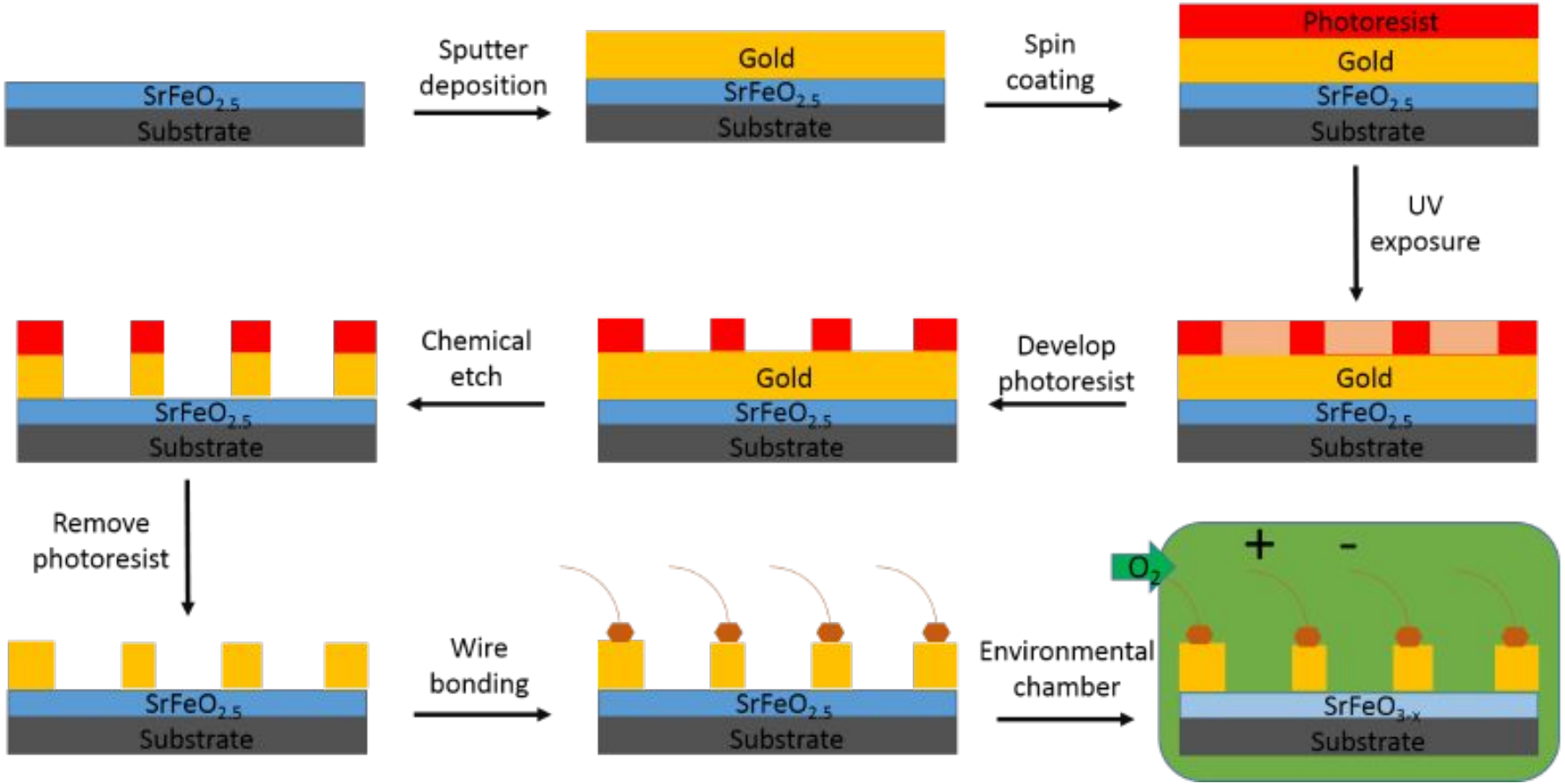
- Techniques to etch away or deposit material in microscale patterns
- Basis for semiconductor devices, MEMS, etc.




***Goal:*** *Fab acoustic metamaterials of 1D chain, graphene, TBG in lithium niobate*

Daniel Shen

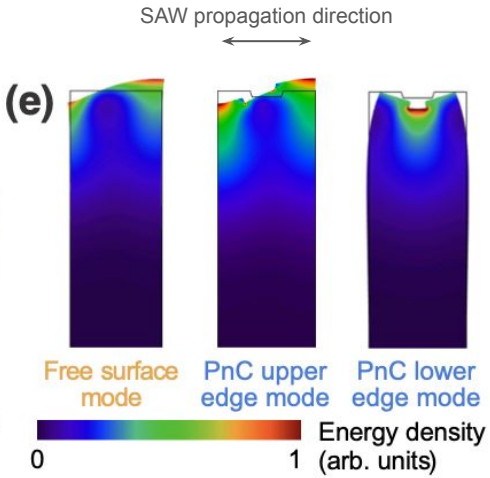

SrFeO2.5
Substrate
Sputter deposition
Gold
SrFeO2.5
Substrate
Spin coating
Photoresist
Gold
SrFeO2.5
Substrate
UV exposure
Gold
SrFeO2.5
Substrate
Develop photoresist
Gold
SrFeO2.5
Substrate
Chemical etch
SrFeO2.5
Substrate
Remove photoresist
SrFeO2.5
Substrate
Wire bonding
SrFeO2.5
Substrate
Environmental chamber
O2
+
-
SrFeO3-x
Substrate

# First step: LiNbO3 1D chain (Shao et al., 2019)

*Goal: Replicate 1D chain ("phononic crystal," or PnC) in LiNbO3*

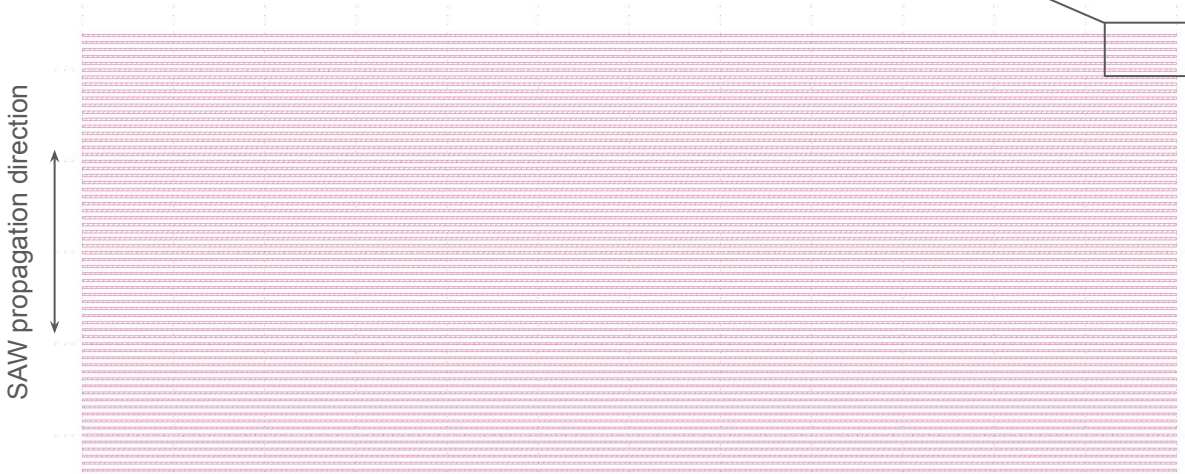
*Purpose: Practice fabrication, develop testing techniques*

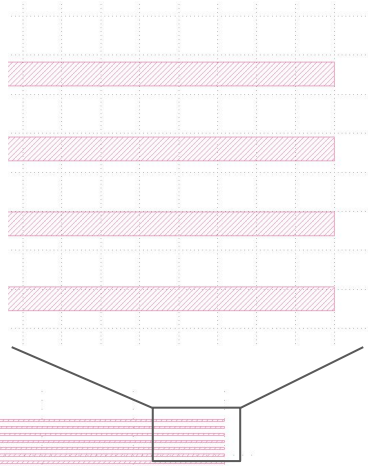
Unit cell (cross section):




Many unit cells (top-down view):

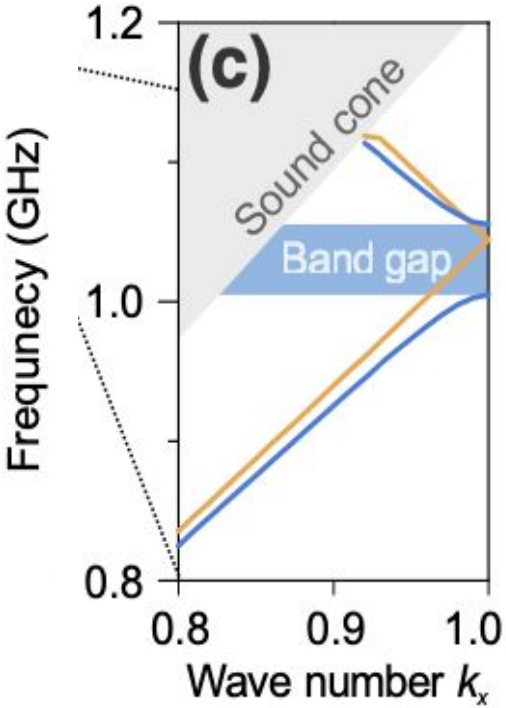
pink = **etched** grooves



Daniel Shen

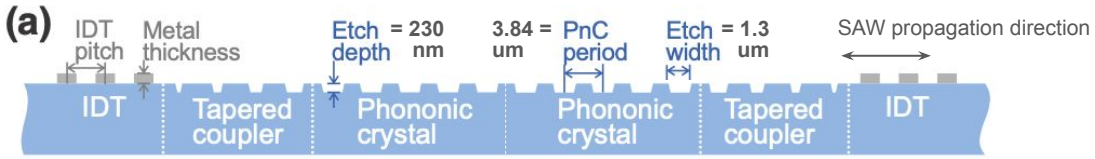
# PnC band structure




- Blue line is the 1D chain/PnC's band structure
- Bandgap, as expected — same as in quantum 1D chain and air cavity-channel acoustic metamaterials

# PnC device

Overall device (cross-section):

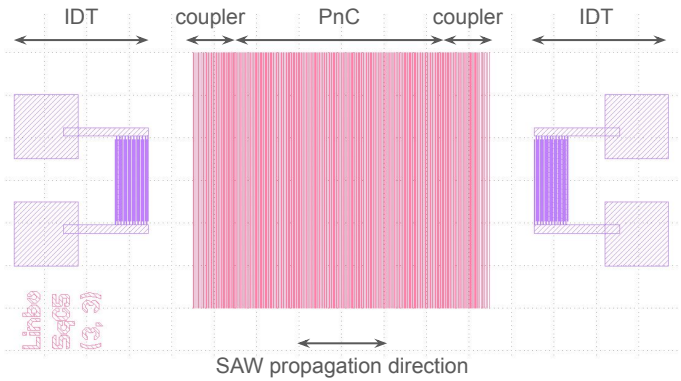


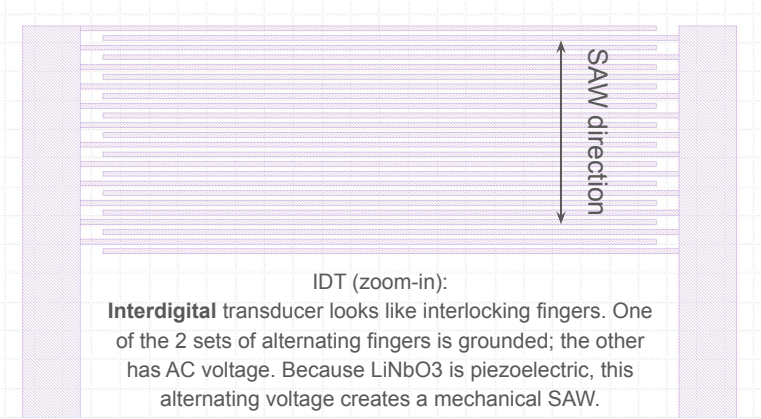

IDT (interdigital transducer): emit and receive wave

**PnC: periodic grooves etched out of surface**

Coupler: gradual change in width reduces reflectance

Overall device (top-down view): purple = **deposited** metal




IDT (zoom-in):
**Interdigital** transducer looks like interlocking fingers. One of the 2 sets of alternating fingers is grounded; the other has AC voltage. Because LiNbO3 is piezoelectric, this alternating voltage creates a mechanical SAW.

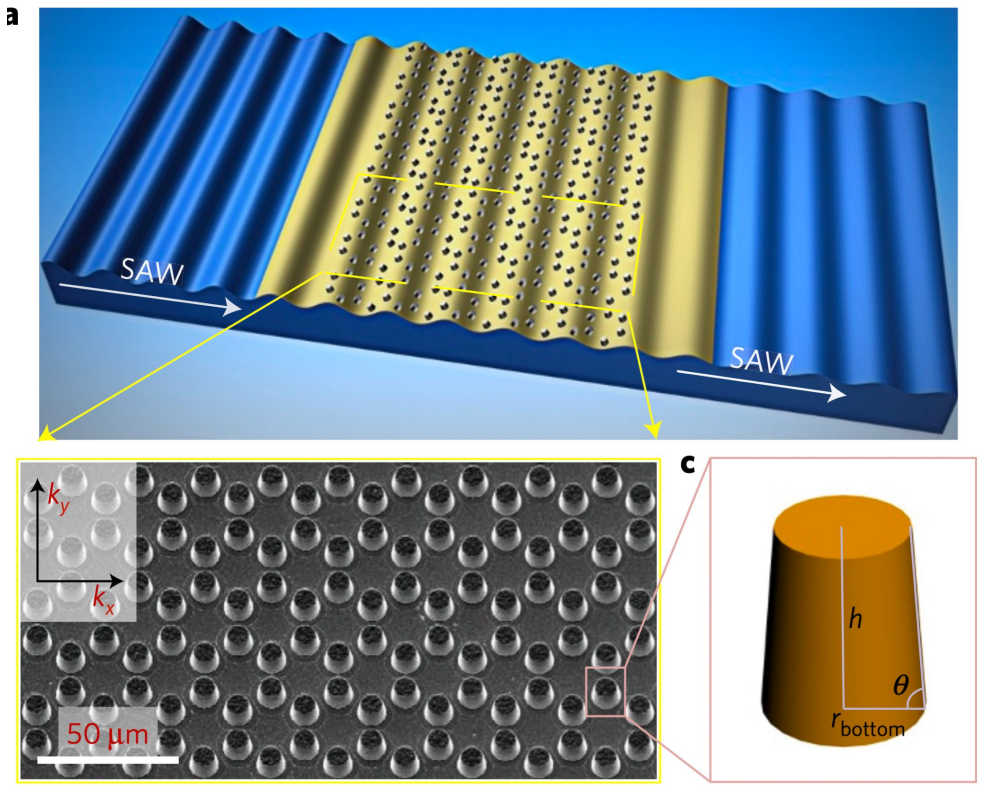
# Chip design

Picture of chip
(only etched grooves,
no IDT's yet):

# Future: LiNbO3 graphene metamaterial (Yu et al., 2016)

Yu et al., 2016:

Gold pillars on lithium niobate



# Current progress on PnC

- Have developed process/recipe for etching grooves
- About to try first IDT metal deposition
- Future step: connect IDT's to voltage & measure transmission to look for bandgap

# What I've learned from this project

Hard skills

- Microfabrication processes: photolithography, etching, wet bench, dose testing, image analysis, purchasing materials
- Pattern design in Python, phidl, KLayout

Soft/research skills

- Dealing with setbacks; e.g., failure to etch, chip cracking, material purchase delays
- Trial and error

# Tues, Oct 4

**Daniel (5 min):** Got thermal evaporation materials, did first IDT deposition on dose testing chip and will soon optically inspect, started new final chip

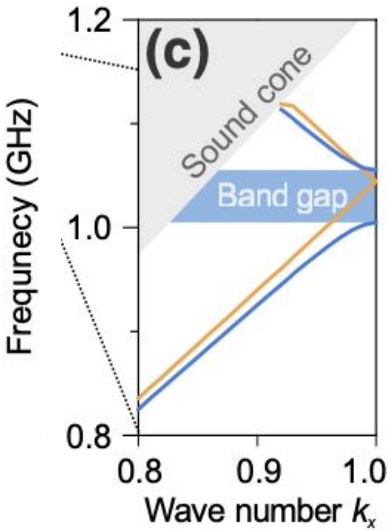
- IDT deposition: 15 nm Cr, 200 nm Au
- Metal evaporation covers entire chip
  - “Liftoff” process (today) removes metal that was deposited on resist, leaving only metal on areas not covered by resist (which is where IDT’s were defined)
- New final chip
  - Have exposed and developed mask for groove etching

Chromium/gold-plated chip:

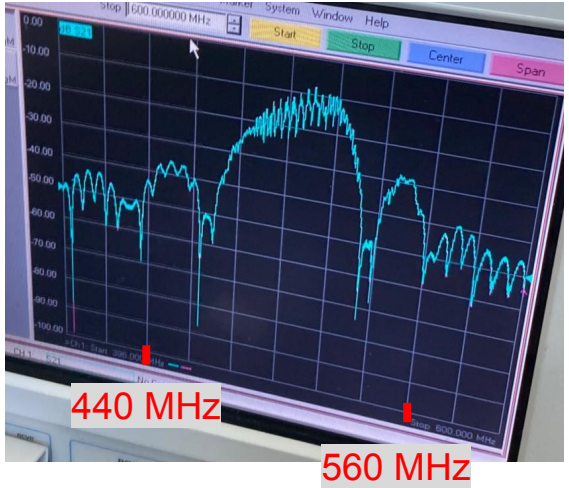
# Tues, Nov 15

**Daniel (10 min):** recap of 1D chain bandgap, seen in transmission study

Theoretical:




Free surface transmission:




1D chain transmission:

COMSOL

- Working on acoustic pillar graphene, yet to complete GKMG sweep and compare to real graphene
- Next step; ask Ben/Jenny: can we plot/measure electric potential and see if cantilever can pick that up?

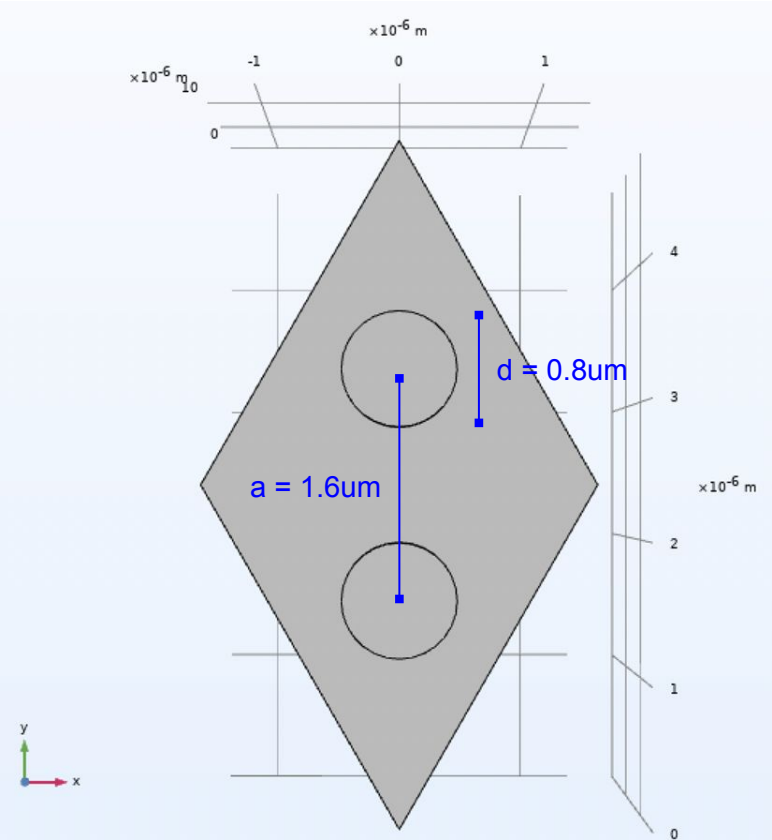
Fab considerations

- Rationale for feature sizes due to various constraints
  - OL-11 resolution minimum: >600nm horizontal feature size
  - Want ≥1:1 aspect ratio for pillars: >600nm depth
  - >600nm depth is pushing bounds for etching. Etching typically goes up to ≲1um before resist starts heating up too much. Deposition of AlN could avoid this problem, but may be technically more involved/newer
- Deposition (David chat)
  - Sputtering may be best bet (in CNS)
  - MBE (Jenny) — Wikipedia says epitaxial growth on silicon
  - ALD (some other group), or some other technique from Capasso group with $TiO_2$?
  - David: for AlN(?) on diamond, Loncar tried to have undergrad figure out in-house fab but didn't succeed; they ship this out

# 11/29

LiNbO3 pillar graphene: COMSOL updates, initial fab considerations

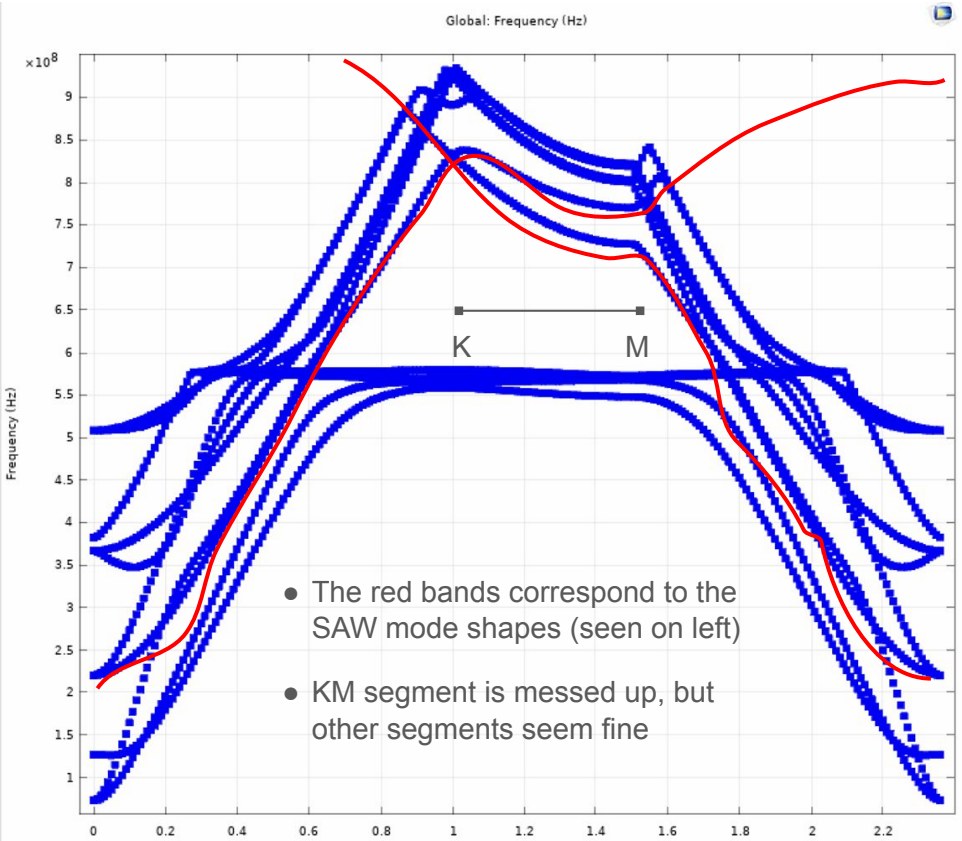
# Unit cell of pillar graphene




Parameters determined by constraints:

- Minimum width of etched-away space (everything beside pillars) > lithography resolution
  → a-d > 0.6um
- Etch depth < 1um and >1:1 aspect ratio constraint
  → d < 1um
- Cylinder isn't too small or large
  → d/a ~ 0.5

# COMSOL: fixed Floquet periodicity, still bad KM bands



# Next steps: COMSOL KM band fix, KM fab considerations

COMSOL KM band fix

- The flatness at the M point is correctly replicated. But the problem is the monotonic frequency decrease in both bands
- This could be due to LN's anisotropic crystal structure. We're not changing the crystal orientation as we change the k-vector's direction (monotonically), causing the dispersion relation to also change (monotonically)
- Next step: rotate geometry along with k (rotating material properties by doing matrix rotation multiplications seems to be a big hassle)

KM fab considerations

- Similarly, on the chip, we'll need to create a separate structure for each k-vector direction in the KM segment

# 12/9

Group meeting: LiNbO3 PnC & pillar graphene

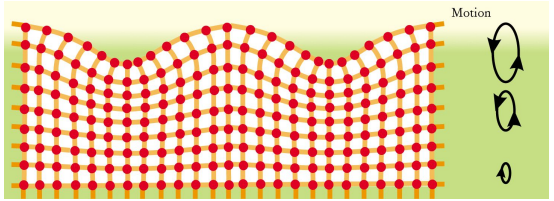
# Lithium niobate metamaterials

Lithium niobate ($LiNbO_3$)

- Used in telecom for acoustic/optical modulators
- Large piezoelectric coupling

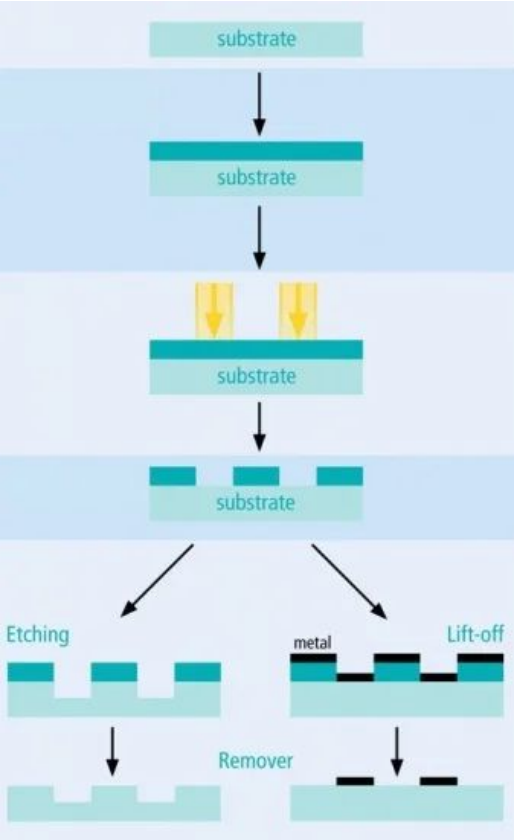
Surface acoustic waves (SAW)

- Confined to surface, depth of ~1λ
- Analog to air pressure waves in air cavity-channel metamaterials




***<u>Goal: Create 1D chain, graphene, TBG metamaterials harnessing SAW in LiNbO3</u>***

# Nanofabrication: method of making LiNbO3 metamaterials




Nanofabrication (“fab”)

- Techniques to etch away or deposit material in microscale patterns
- Basis for semiconductor devices, MEMS, etc.

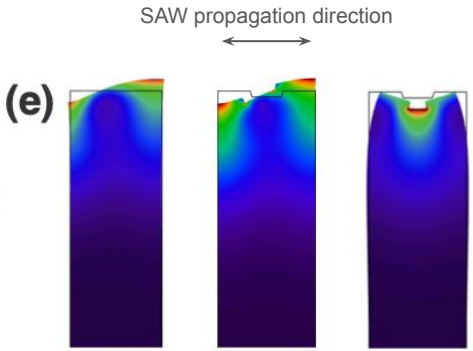
3 basic techniques

1. Photolithography: layers “resist” mask which exposes (does not cover) area of interest, and protects (covers) rest of substrate — for etching or deposition
2. Etching (dry): argon plasma cuts away substrate material
3. Deposition: evaporates metal onto substrate

# Step 1: LiNbO3 1D chain (Shao et al., 2019)

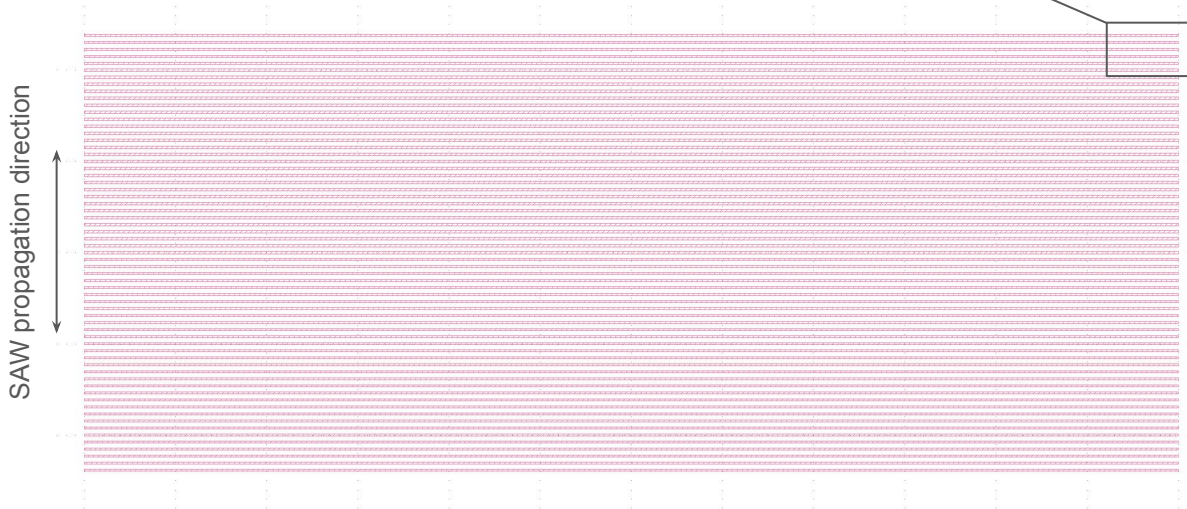
*Goal: replicate 1D chain ("phononic crystal," or "PnC") in LiNbO3*
*Purpose: practice fabrication, develop testing techniques*

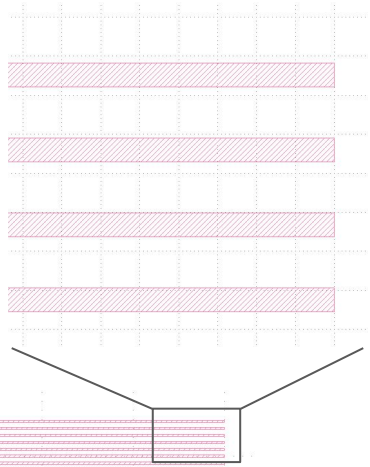
Unit cell (cross section):



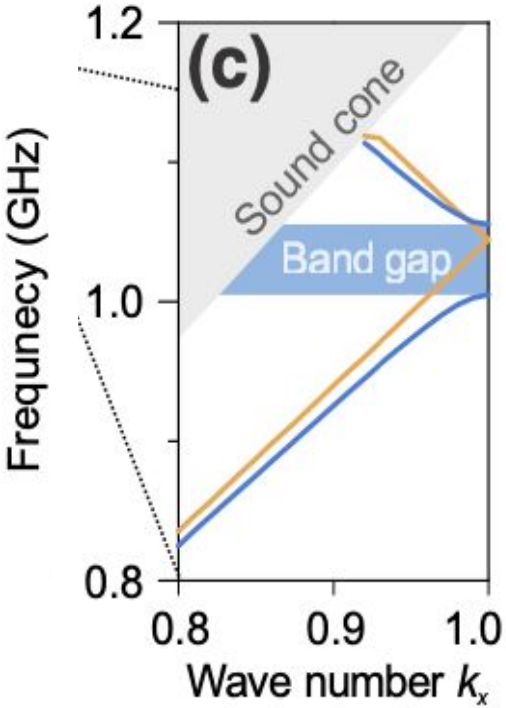

(Various mode shapes)

Many unit cells (top-down view):
pink = **etched** grooves



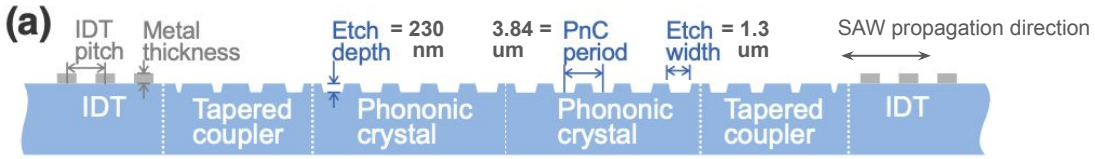
# PnC band structure




- Blue line is the 1D chain/PnC's band structure (simulation study by Shao et al. [2019])
- Bandgap; same as expected in quantum 1D chain and air cavity-channel acoustic metamaterials

# PnC device

Overall device (cross-section):



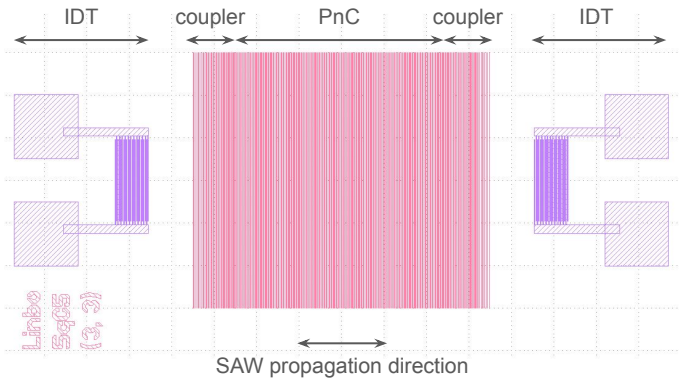

IDT (interdigital transducer): emit and receive wave

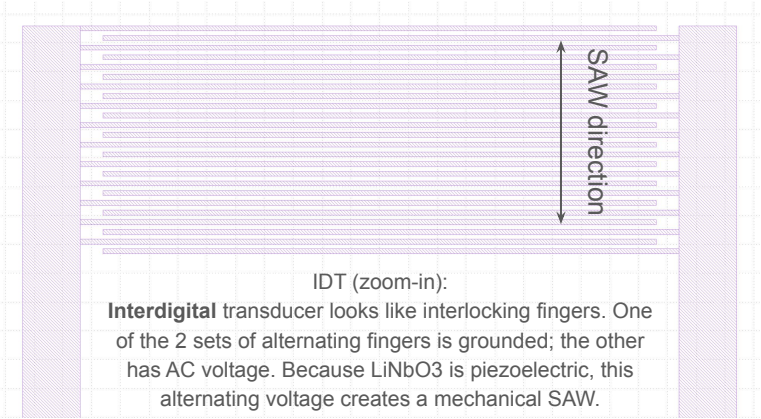
**PnC: periodic grooves etched out of surface**

Coupler: gradual change in width reduces reflectance

Overall device (top-down view):

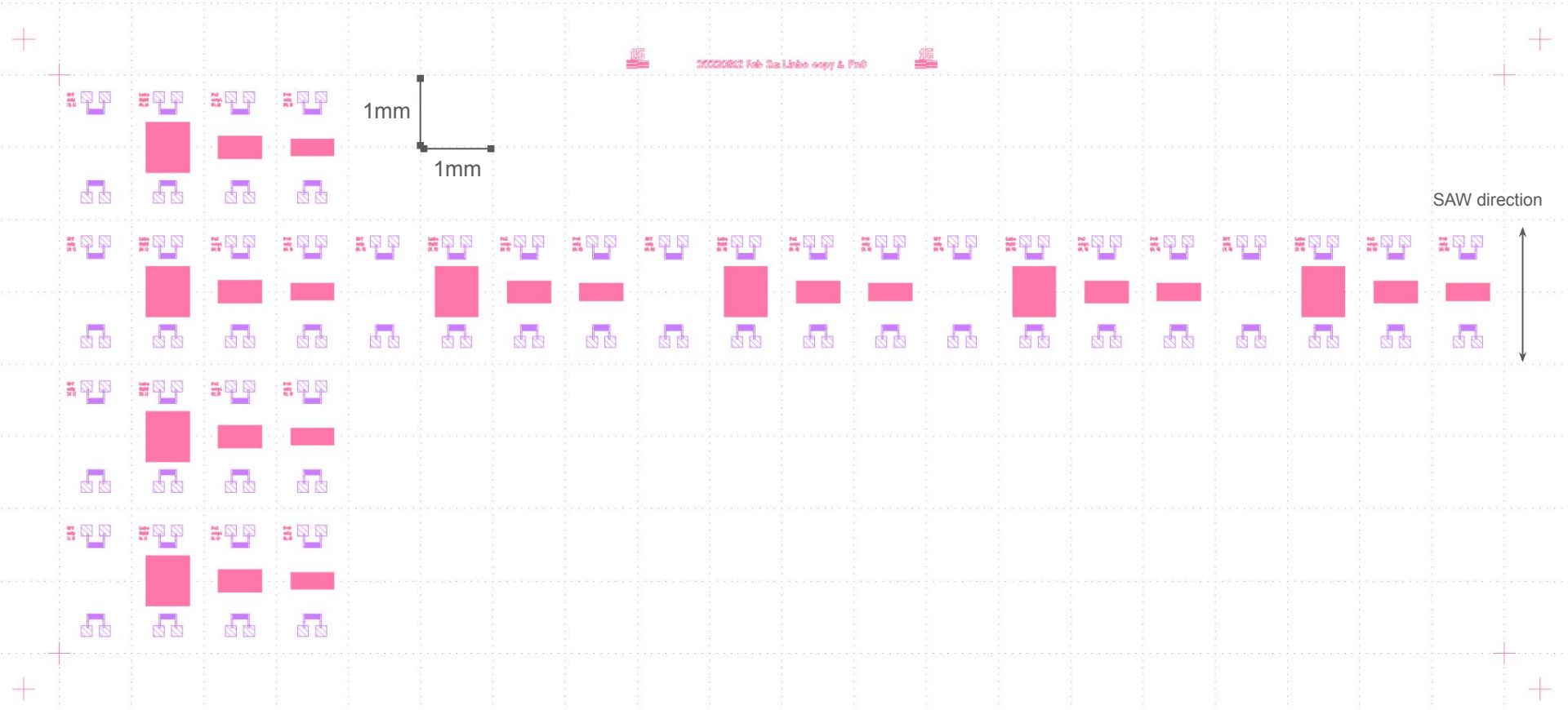
pink = etch
purple = **deposited** metal



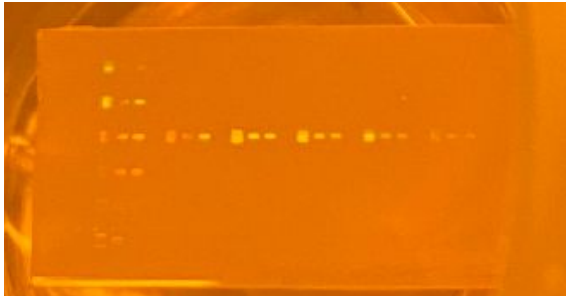

IDT (zoom-in):
**Interdigital** transducer looks like interlocking fingers. One of the 2 sets of alternating fingers is grounded; the other has AC voltage. Because LiNbO3 is piezoelectric, this alternating voltage creates a mechanical SAW.

# Chip design

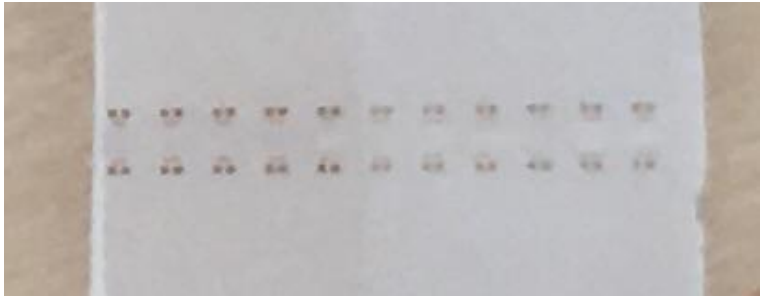


# Fab pictures

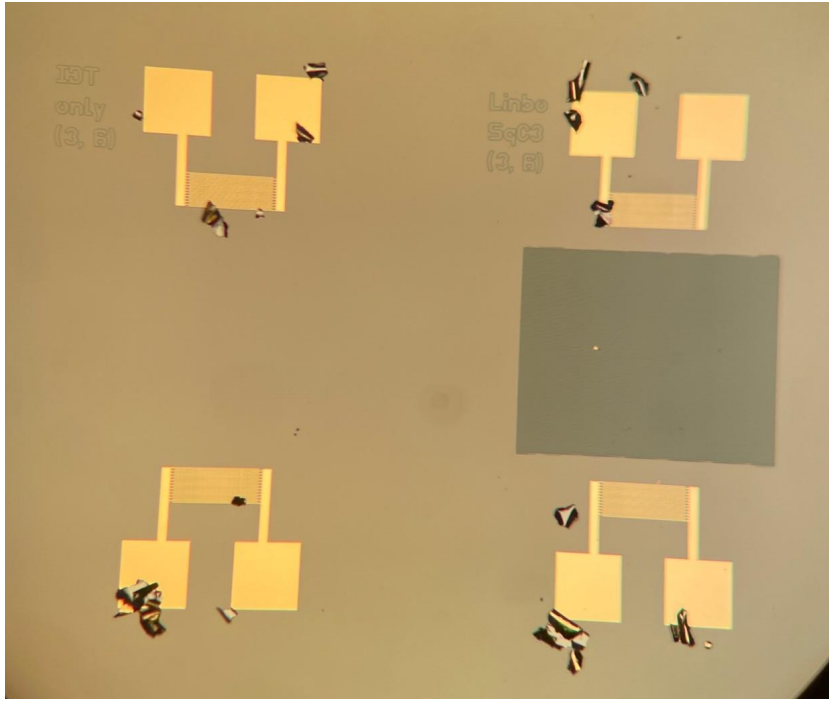
Etched grooves



IDT's



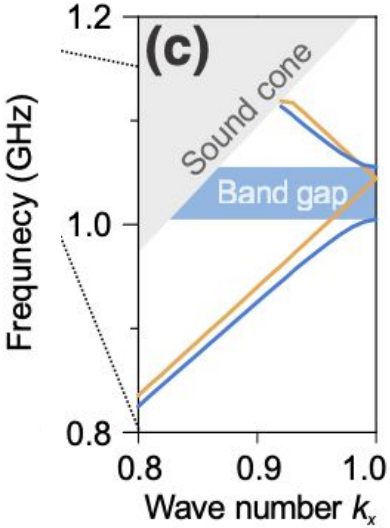
Under microscope



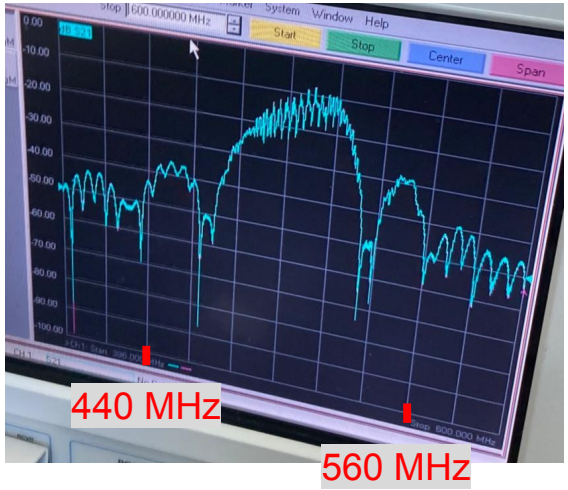
# Successful transmission study on PnC

- Using VNA, applied voltage to one IDT and received signal on other IDT
- Bandgap seen! (We doubled all feature sizes, so frequencies are halved)

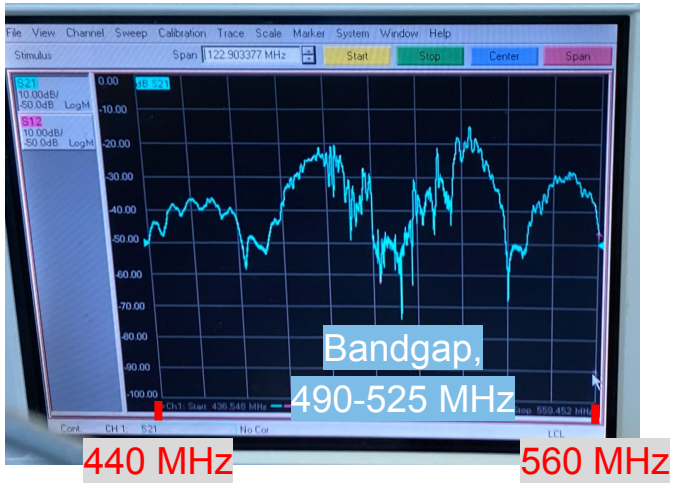
Theoretical:




Free surface transmission:




1D chain transmission:

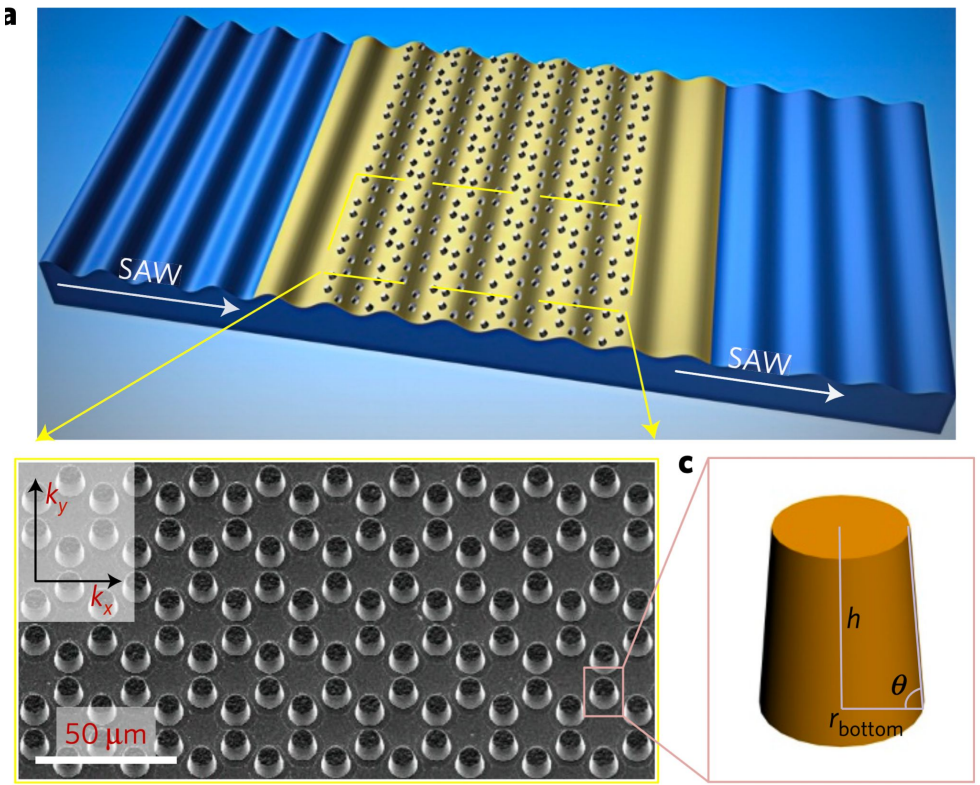


# Step 2: LiNbO3 graphene metamaterial (Yu et al., 2016)

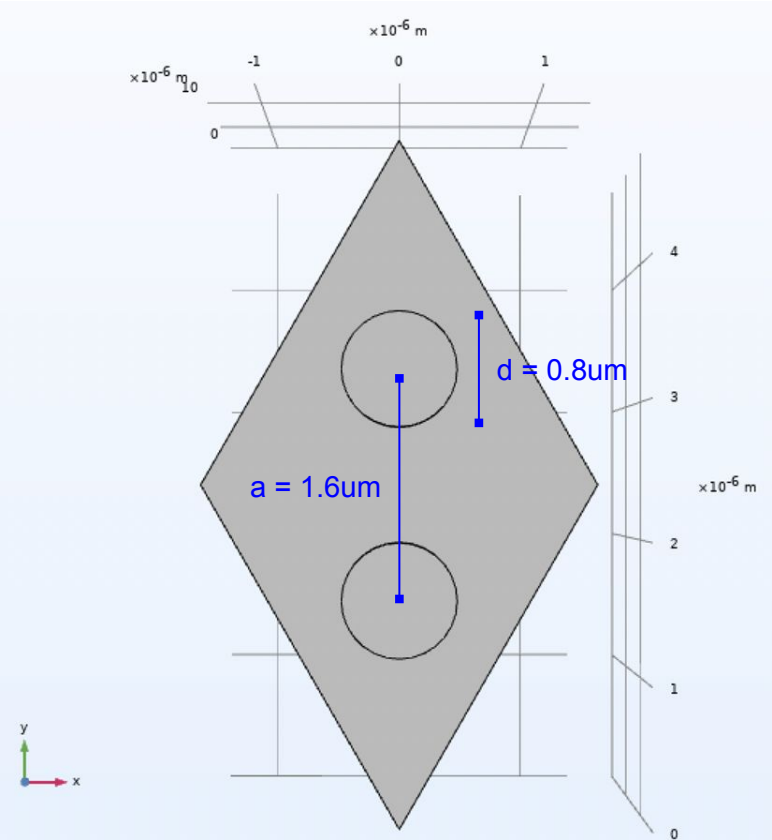
Yu et al., 2016: honeycomb-lattice gold pillars on LiNbO3

*First approach: LiNbO3 pillars (on LiNbO3), for ease of fabrication (etching only, no deposition)*

*Purpose: practice fabrication for TBG (which may look like two graphenes stacked back-to-back)*



# Unit cell of pillar graphene (top-down view)

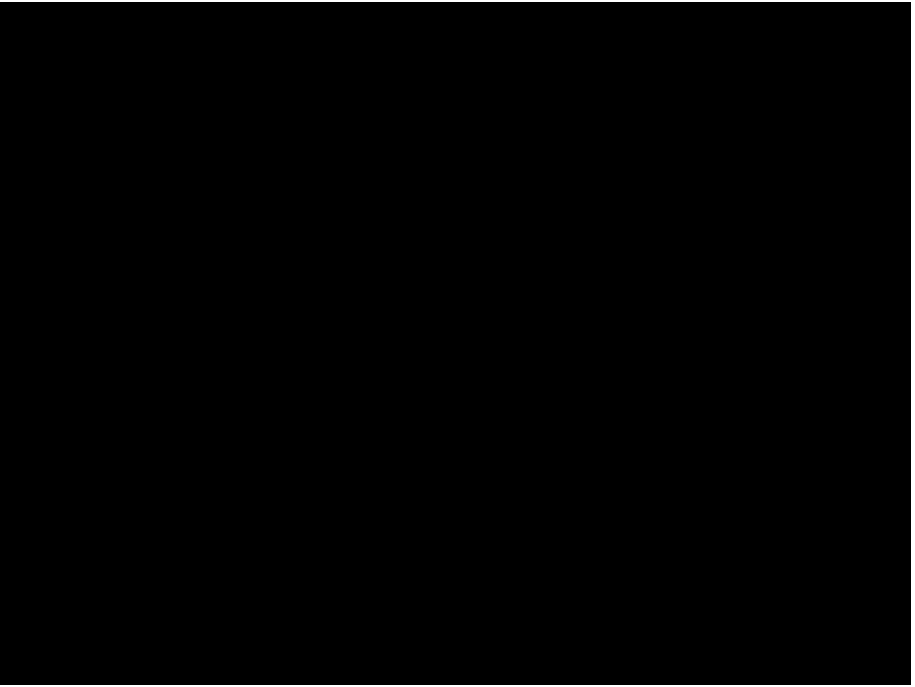


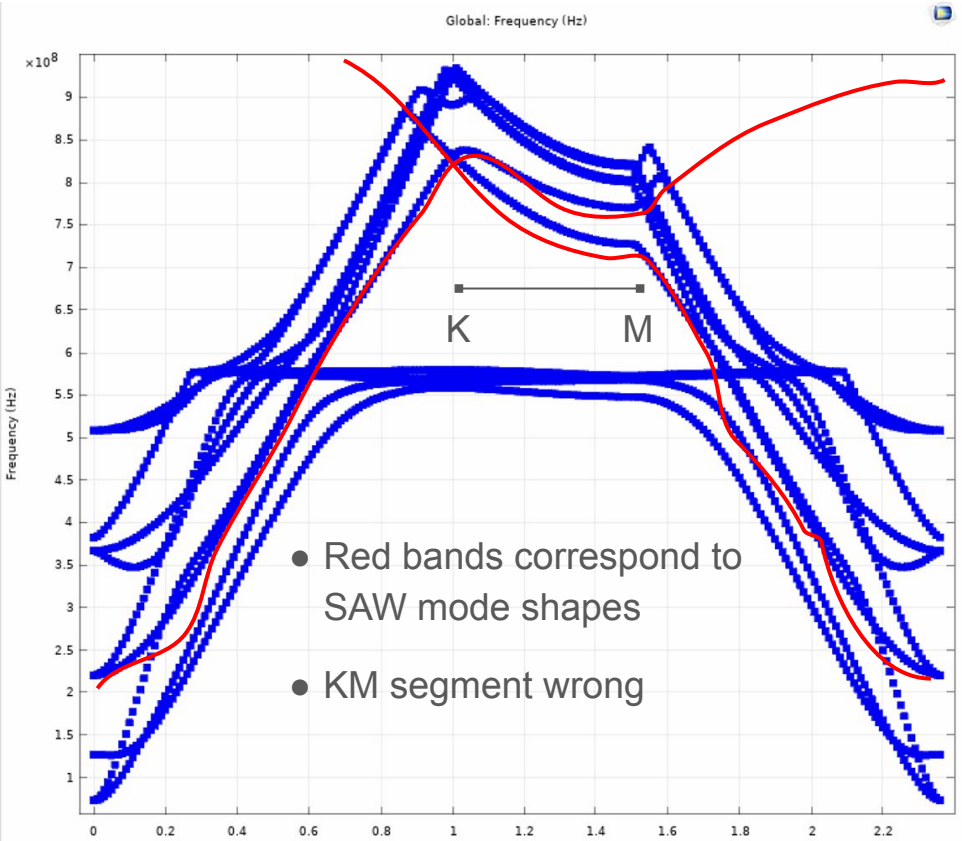

Parameters constrained by:

- Minimum width of etched-away space (everything beside pillars) > lithography resolution
  → a-d > 0.6um
- Etch depth < 1um and >1:1 aspect ratio constraint
  → d < 1um
- Cylinder isn't too small or large
  → d/a ~ 0.5

# COMSOL band structure

SAW simulation





# Next steps

COMSOL KM segment fix

- Incorrect band structure is likely due to LN's anisotropic crystal structure
  - Waves in different directions have different dispersion relations
  - KM is the only segment where wave direction is changing
  - Haven't accounted for this in our simulation
- Fix: rotate geometry along with k
- Similarly, on the chip, we'll need to fab a separate structure for each k-vector direction in the KM segment

Fab

- Design chip, plan fab process & reiterate