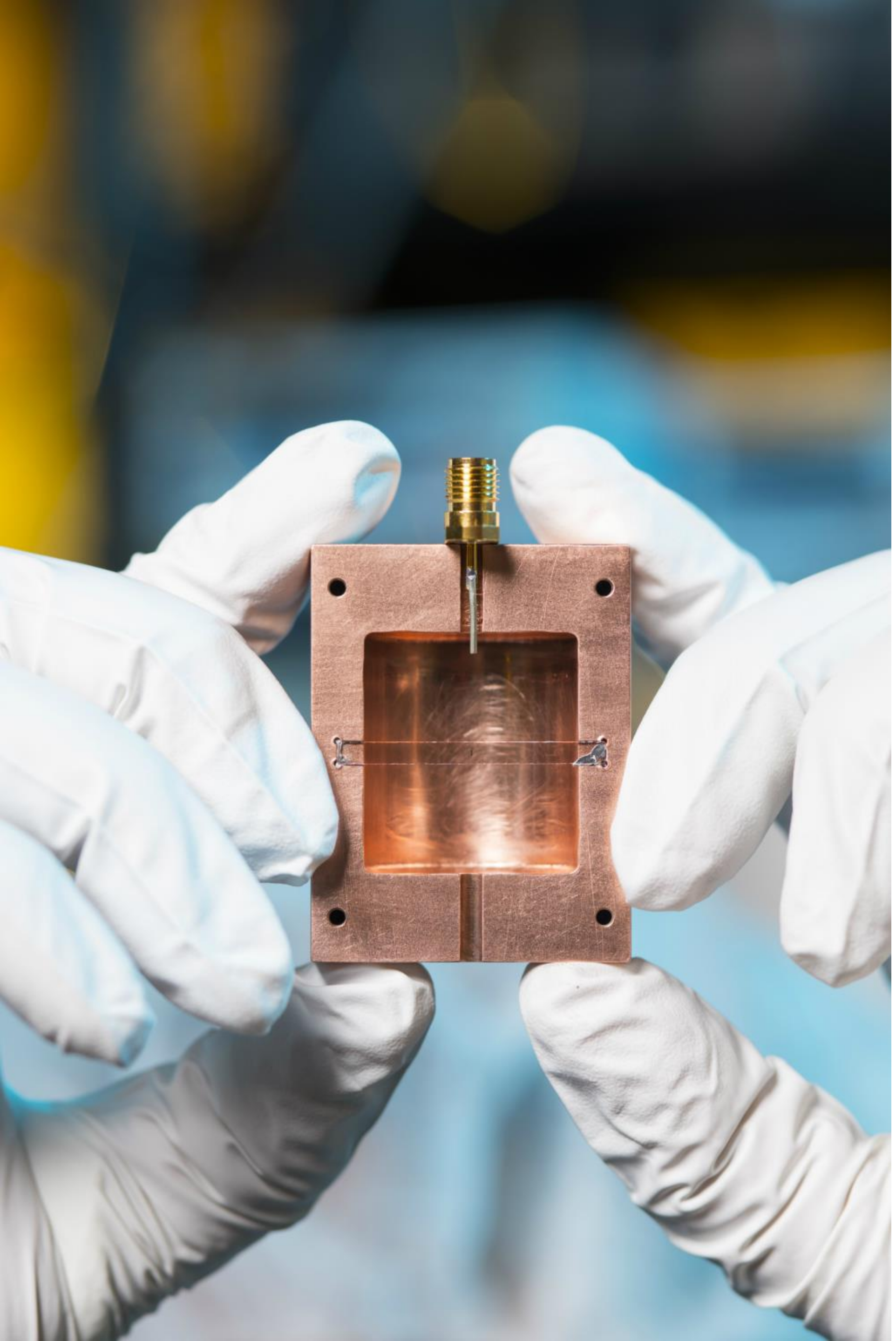

High-Q 3D Photonic Bandgap Cavities for Axion Detection

LLNL Axion Cavity Workshop 2018

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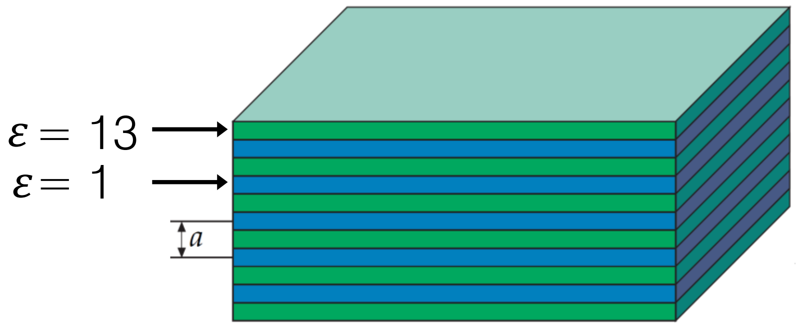
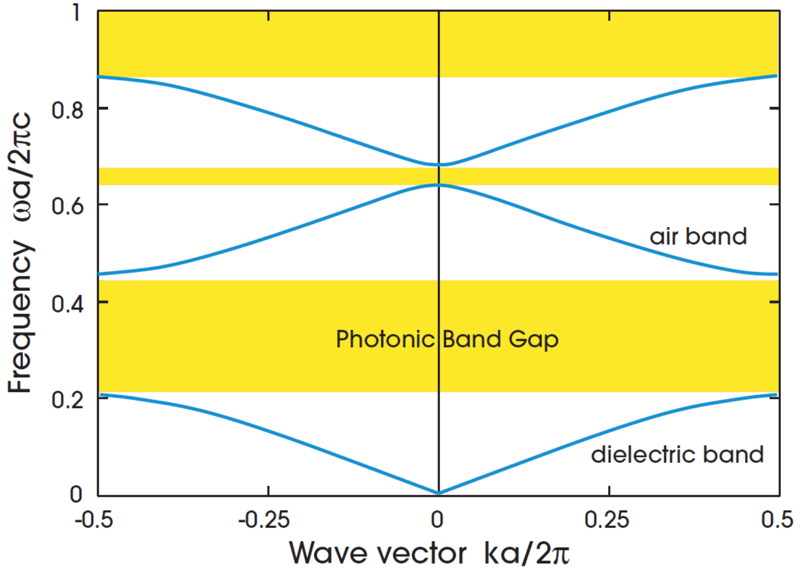
Outline

- Introduction to Photonic Band-gap (PBG) cavities
- Motivation in the context of dark matter axion detection
- Omni-directional PBG cavity
- Simulation results

Photonic Band-gap Material

- Band-structure for photons similar to electrons in semiconducting materials
- Created by periodic arrangement of contrasting dielectric objects (atoms)
- Simplest example is a Bragg reflector in 1-D
- Band-gap size, $\frac{\Delta\omega}{\omega_m} \sim \frac{\Delta\varepsilon}{\varepsilon}$



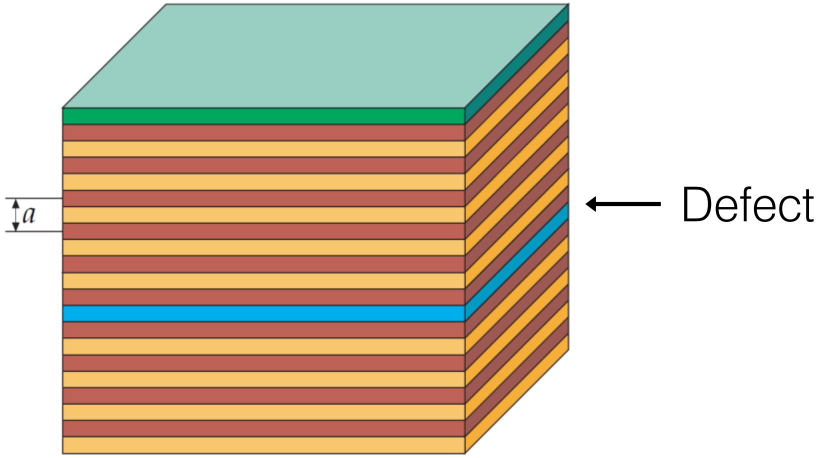


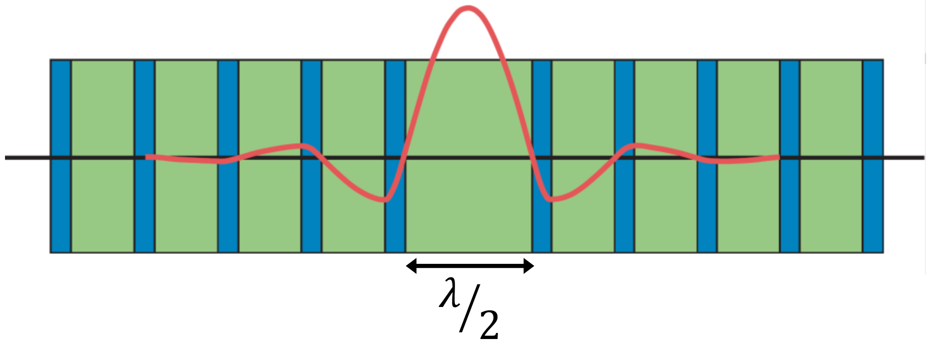
The width of the $\varepsilon = 13$ layer is $0.2a$, and the width of $\varepsilon = 1$ layer is $0.8a$

Joannopoulos, John D., et al. *Photonic crystals: molding the flow of light*. Princeton university press, 2011.

Photonic Band-gap Cavity

- Created by introducing a defect site in the lattice
- If defect mode frequency lies in the band-gap, then it must exponentially decay once it enters the crystal
- Q-values fundamentally limited by the dielectric loss and surface loss at the boundary





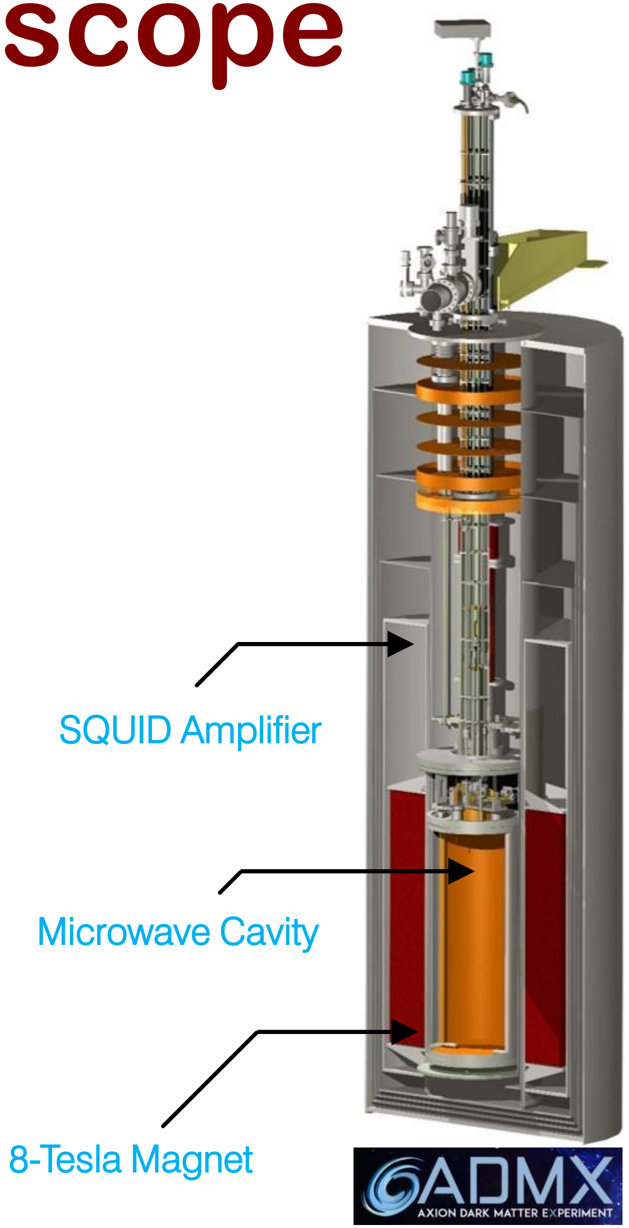
The red curve is the electric field strength of the defect state associated with this structure

Axion Dark Matter Haloscope

- Cold microwave cavity immersed in a strong static magnetic field (~ 8 Tesla)

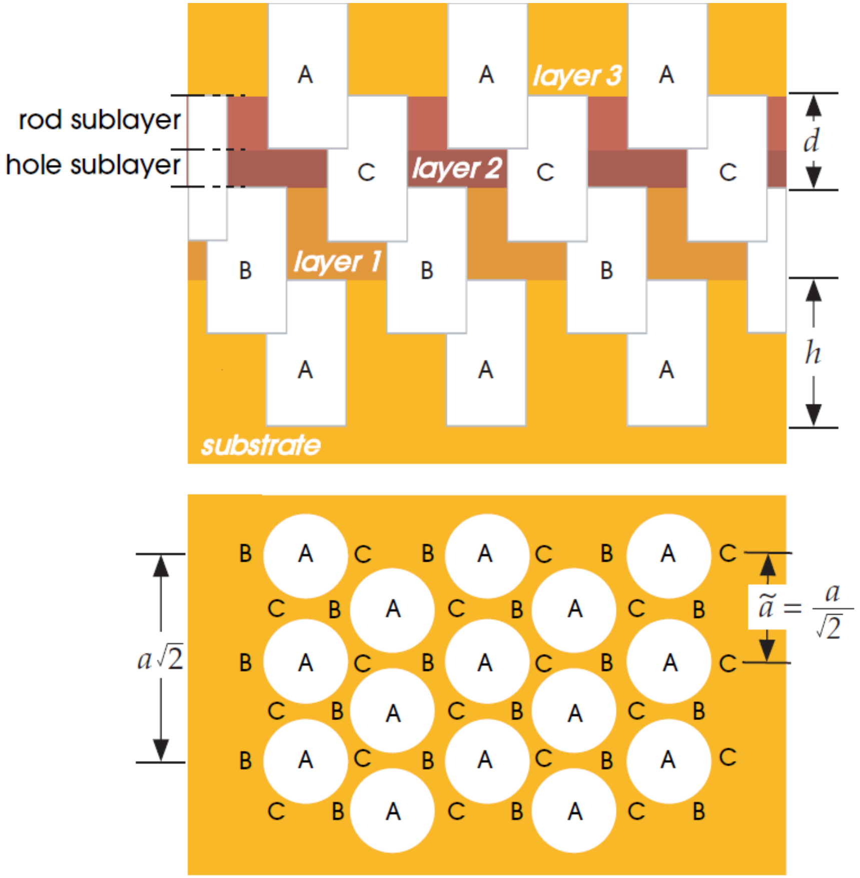
$$\frac{\mathrm{d}N_a}{\mathrm{d}t} \propto B_0^2 Q_{cav} V \propto f^{-\frac{11}{3}}$$

- Superconducting Nb RF cavities with Q~ 10^{10} ☹
- Copper cavities @ 10 GHz, Q ~ 10^4
- High-Q cavities will allow us to
  - Match the readout cadence to the expected signal photon rate
  - Cavity Q in excess of the axion Q can be further used for stimulated emission



Omni-directional PBG Cavity

- FCC-type lattice constructed with Rutile rods (TiO_2) in Sapphire
- Complete confinement of a defect mode in all directions
- Dielectric loss tangent of Rutile and Sapphire is $< 10^{-6}$ thus, Q of 10^6 can be achieved
- Compact structures can be fit into small magnet bores



Johnson, S. G., & Joannopoulos, J. D. (2000). *Applied Physics Letters*, *77*(22), 3490-3492.

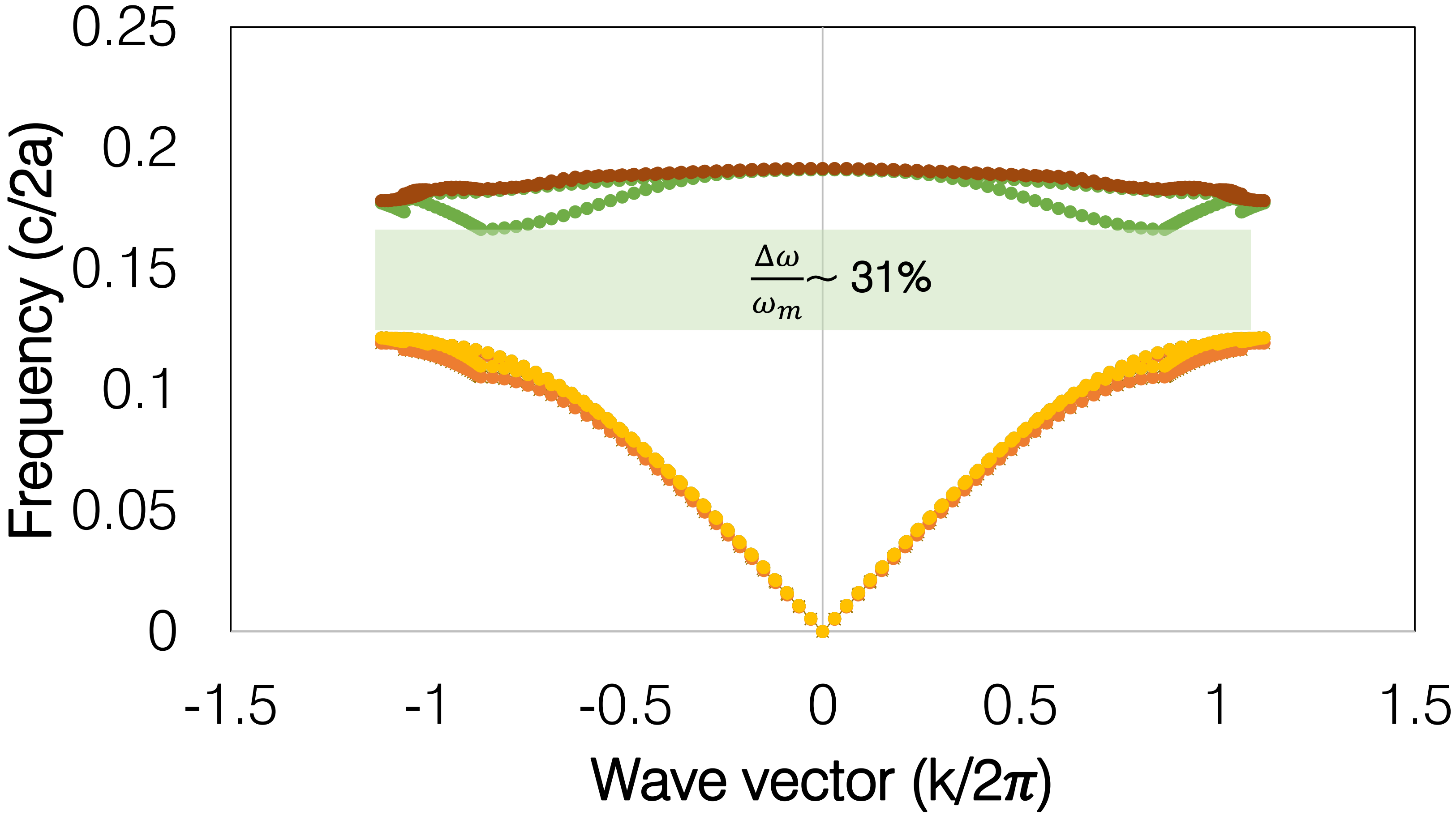
Simulation Results

MIT ***MPB*** simulation package

Rutile rods arranged in a trigonal pattern in Sapphire slab

Dielectric constant (ε):
Rutile ~ 225 and
Sapphire ~ 10

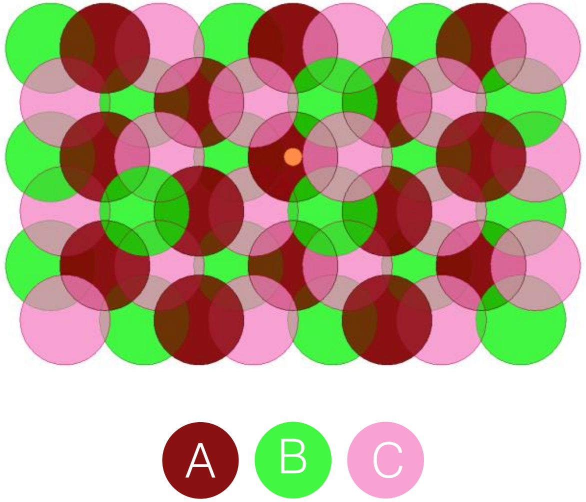
For band-center @ 10GHz,
a ~ 4.11 mm
r ~ 0.293*a* ~ 1.26 mm and
h ~ 0.93*a* ~ 4.0 mm

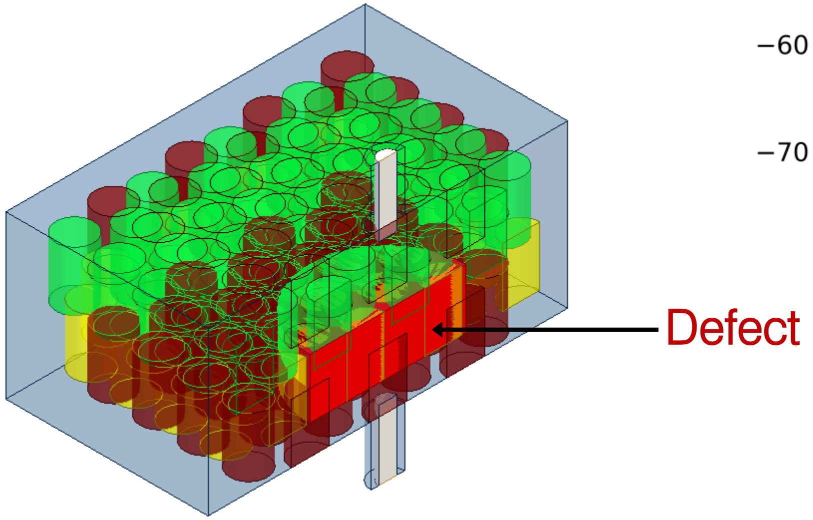


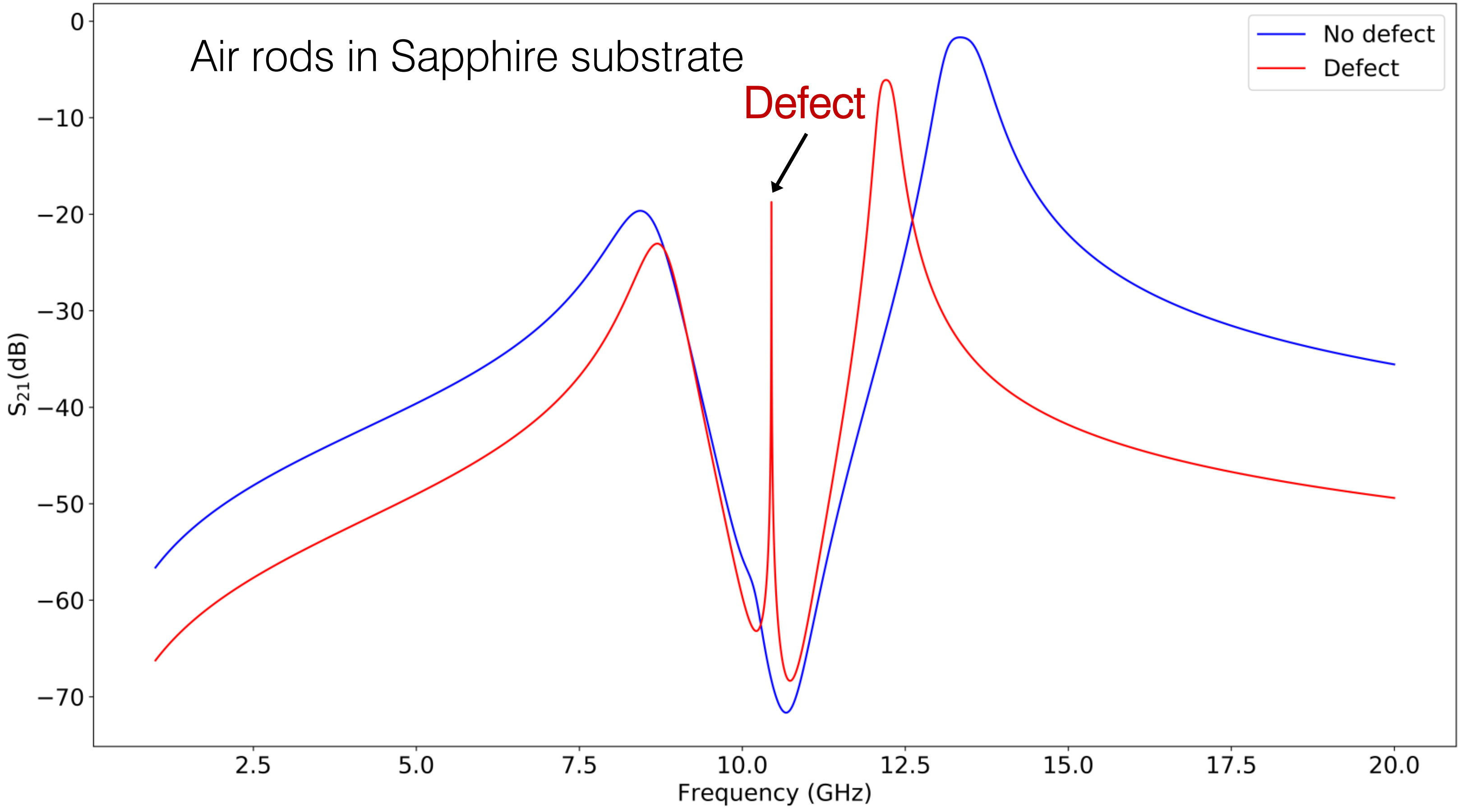
4-5 periods on each side would be sufficient to exponentially suppress the losses at copper walls

Simulation Results

ANSYS HFSS package



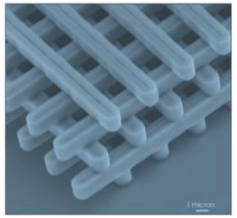




Summary

- PBG Cavities made out of low-loss dielectric material may achieve high Q-values
- High contrast dielectric materials allows compact structure to fit in small magnet bores
- Cavity Q in excess of axion Q will further help in QND measurement using Qubits

Future Work:



- Test powdered form of dielectric materials to estimate the enhancement in Q
- Simulate a woodpile structure (Rutile-Sapphire) to get an idea of Q