Enhanced Light-Matter Interactions in Shape-Engineered Silicon Phononic – Photonic Superlattice Structures

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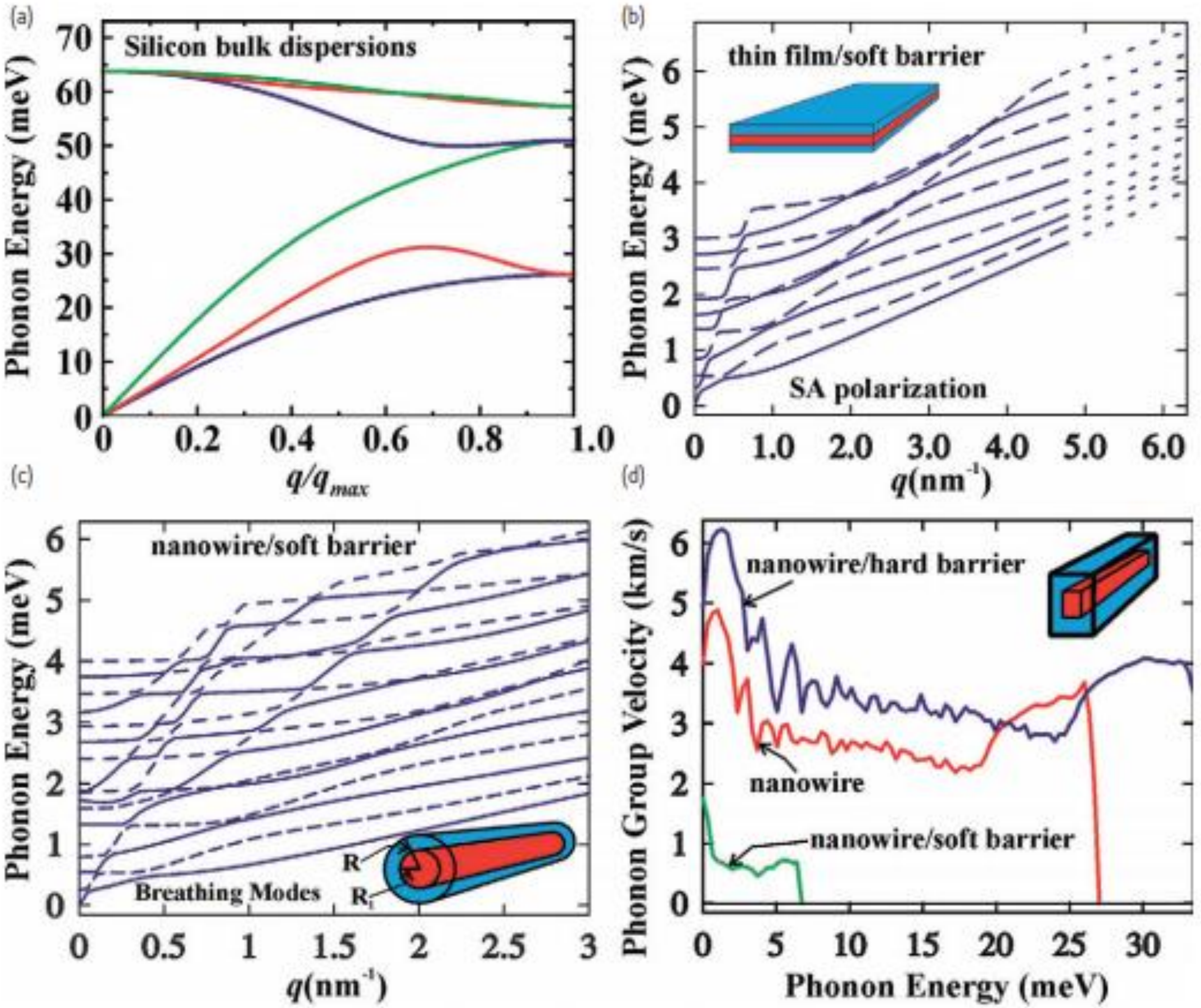
Phononics: From Bulk to Nanostructures



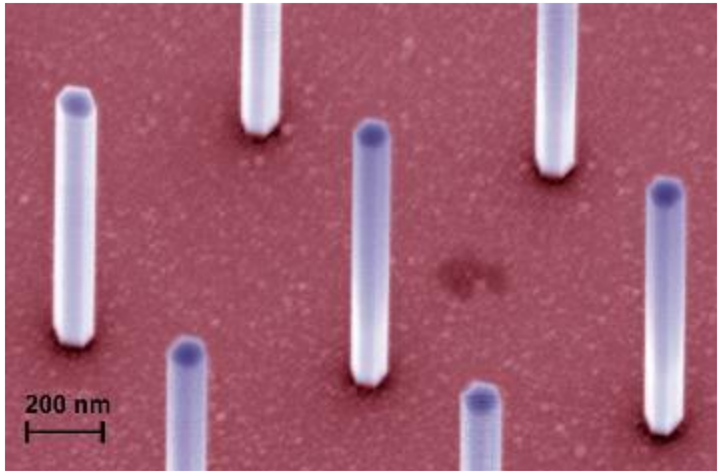
- Similar to electron states, phonon states undergo modification due to confinement effects;
- Appearance of quasi-optical modes;
- Reduction of average group velocity of phonons;
- Vibrational modes with hybrid displacements.

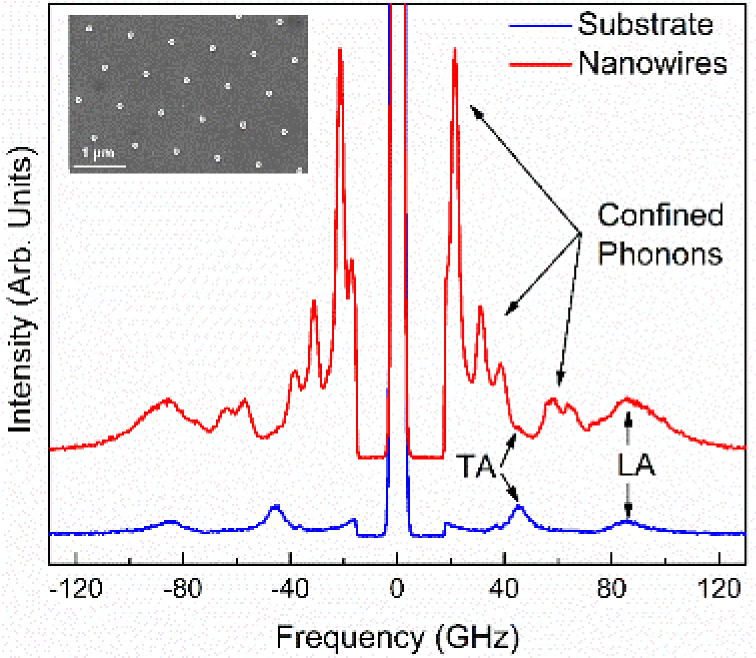
As a result:

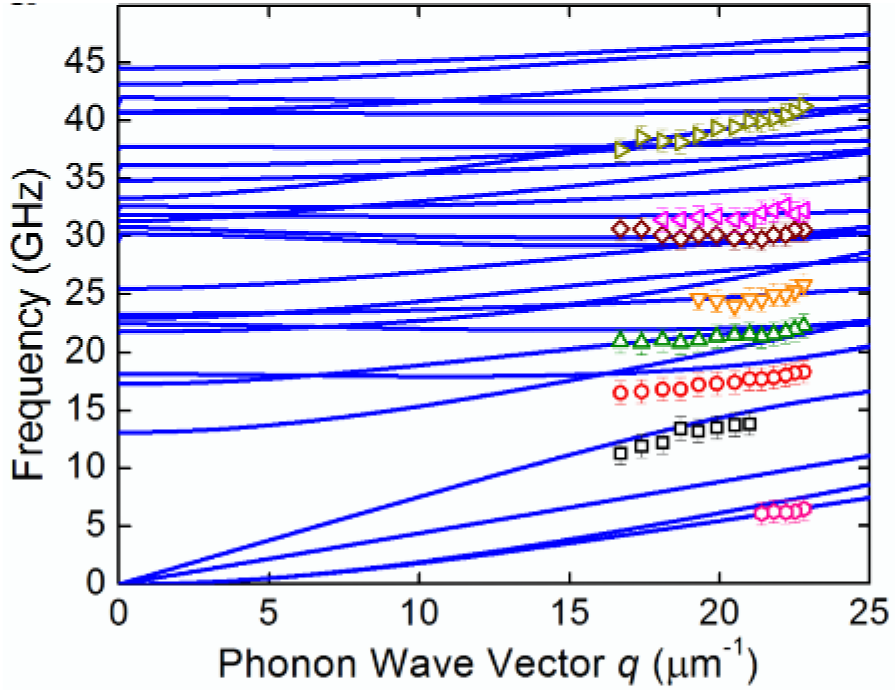
- Changes in thermal properties;
- Phonons scatter electrons and so changes in electronic properties;
- Phonons assist non-radiative optical processes→ can enhance or suppress

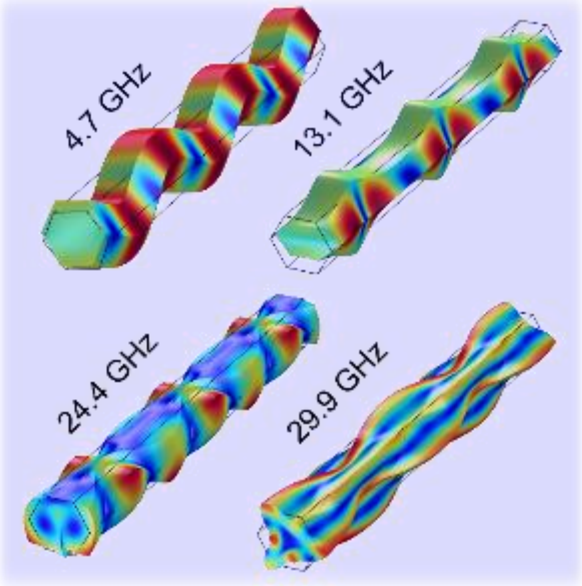
A.A. Balandin and D. L. Nika, *Mater. Today*, vol. 15, no. 6, pp. 266–275, 2012.
J. Zou and A. A. Balandin, J. Appl. Phys. 89, 2932 (2001)

Experimental Observation of Confinement in Individual Structures







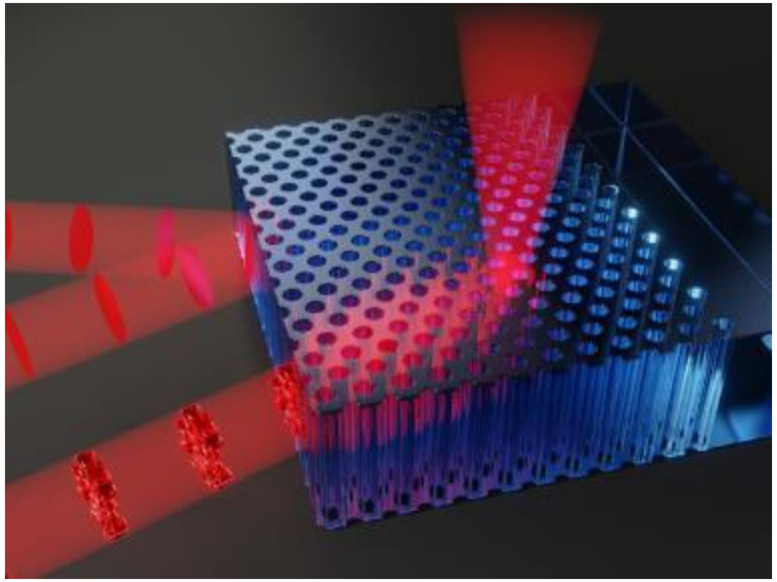


- Experimental observation of phonon confinement in GaAs nanowires;
 Phonons undergo modification because of physical constraints;
- Similar studies have been reported for emmebranes, nanospheres and nanocubes.

Kargar et al. Nat. Commun. 7, 13400 (2016).
Kuok et al., Phys. Rev. Lett. 90, 255502 (2003).
Cuffe et al. Nano Lett. 12, 3569–3573 (2012).

PhoXonics, Photonic and Phononic (X=t+n)

- Photonic crystals: Periodically modulation of the refractive index between their constituents



- Phononic crystals: Periodic variations in their density and elastic properties

Finding common wavelength to modify both concurrently→
Enables the design of PhoXonic structures;

artwork "Órgano" large-scale example of a phononic crystal

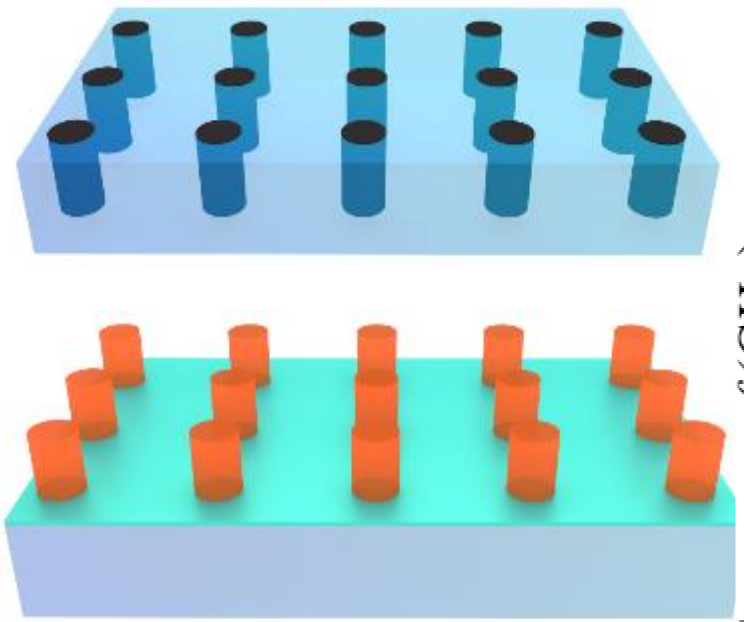
- At specific periodicity, pillar height, and shape one can obtain **both.**
- With engineering phonons and photons one can control the indirect interaction of **light** and **phonons.**

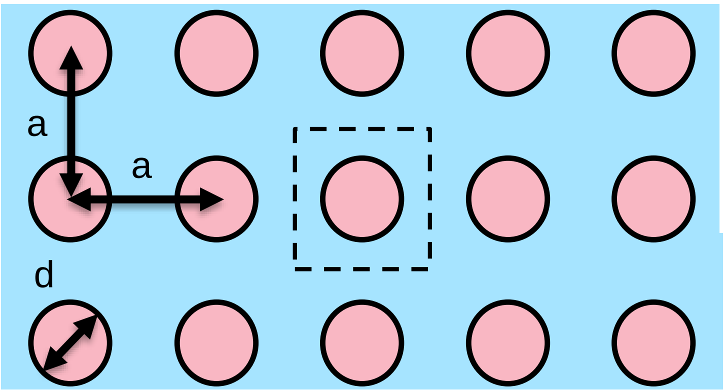
Yudistira et. al, *Phys. Rev. B*, 94, 094304 (2016);; *Hassouani et al., Phys. Rev. B, 82, 155405 (2016)*

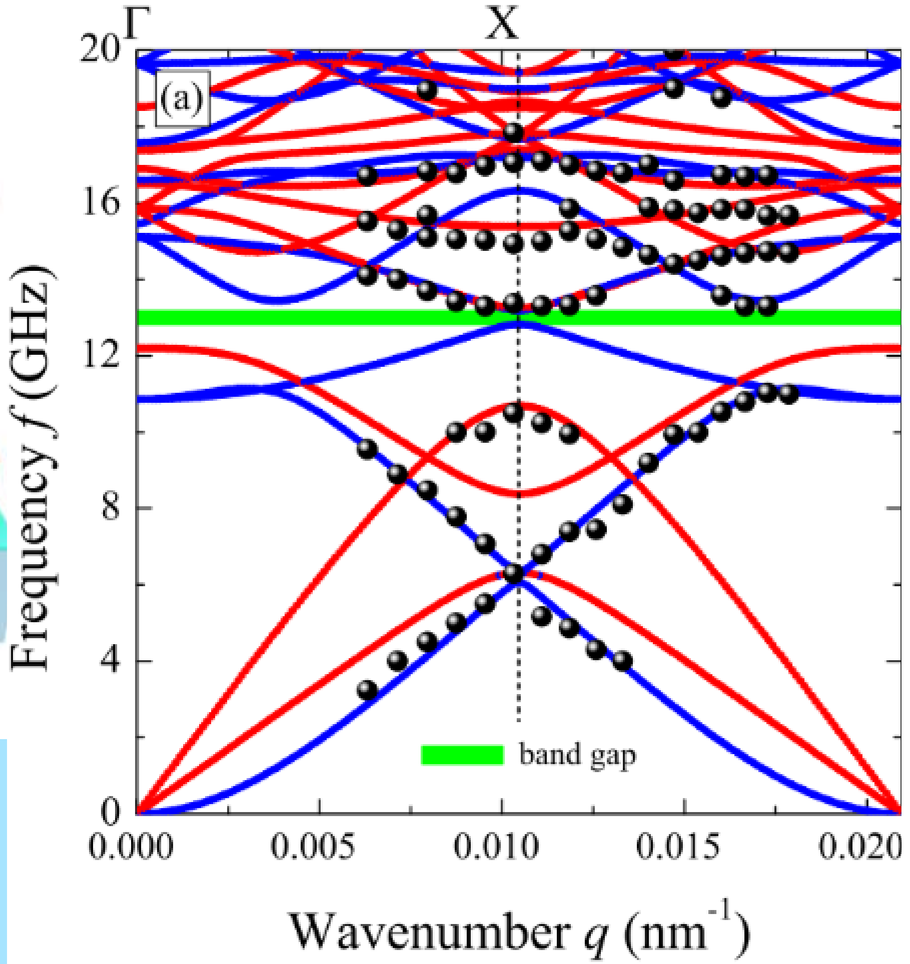
- **Can we fabricate structures with both phononic and photonic functionalities?**

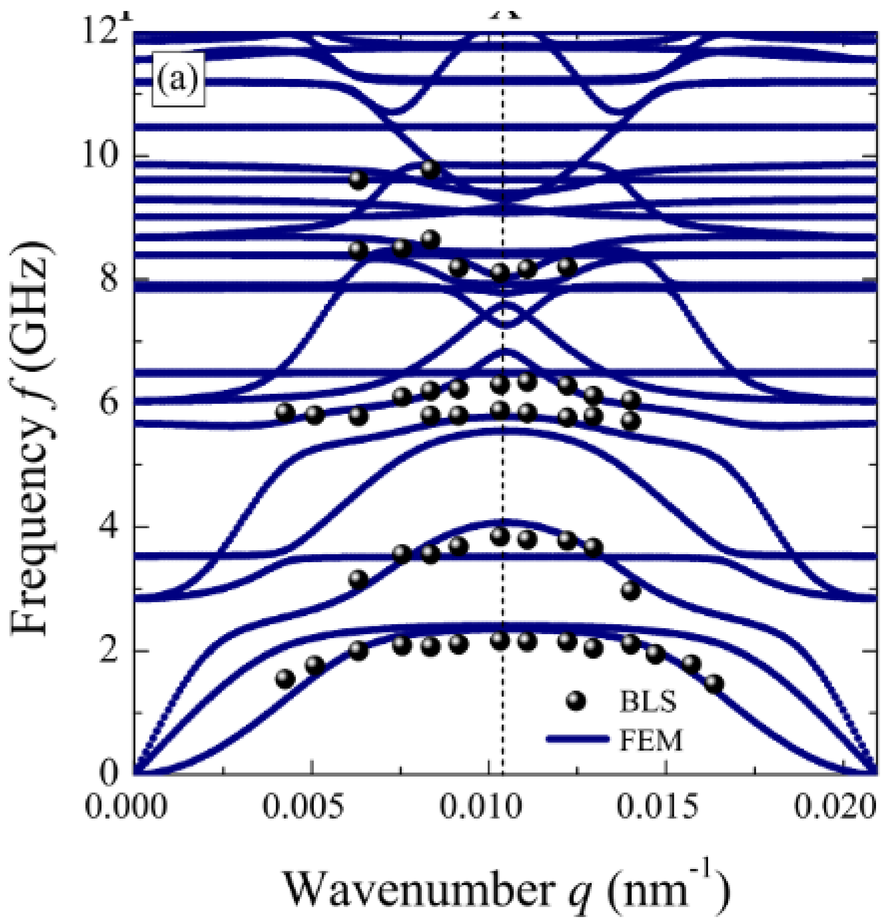
Phononic Crystal: https://en.wikipedia.org/wiki/Acoustic_metamaterial; Photonic Crystal: https://physicsworld.com/a/shaped-light-waves-penetrate-further-into-photonic-crystals/

Phononic Crystals: Phonon Band Engineering





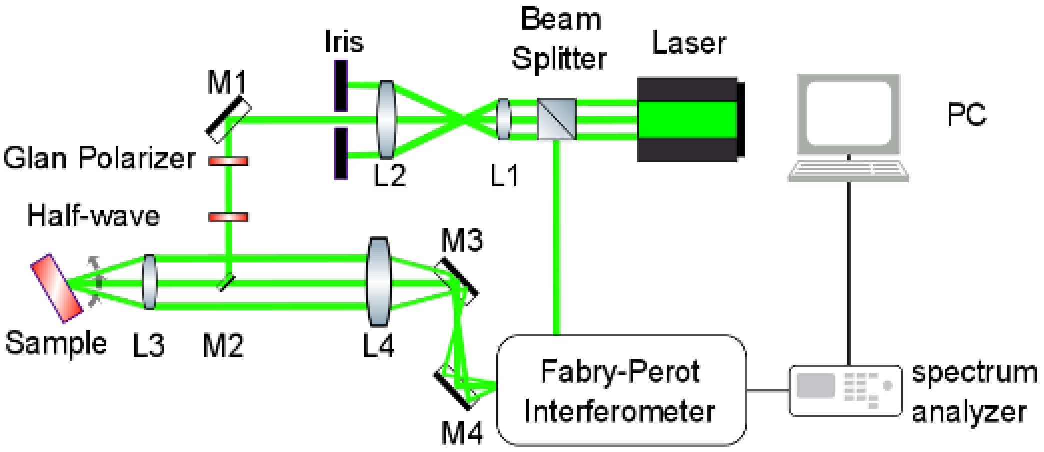


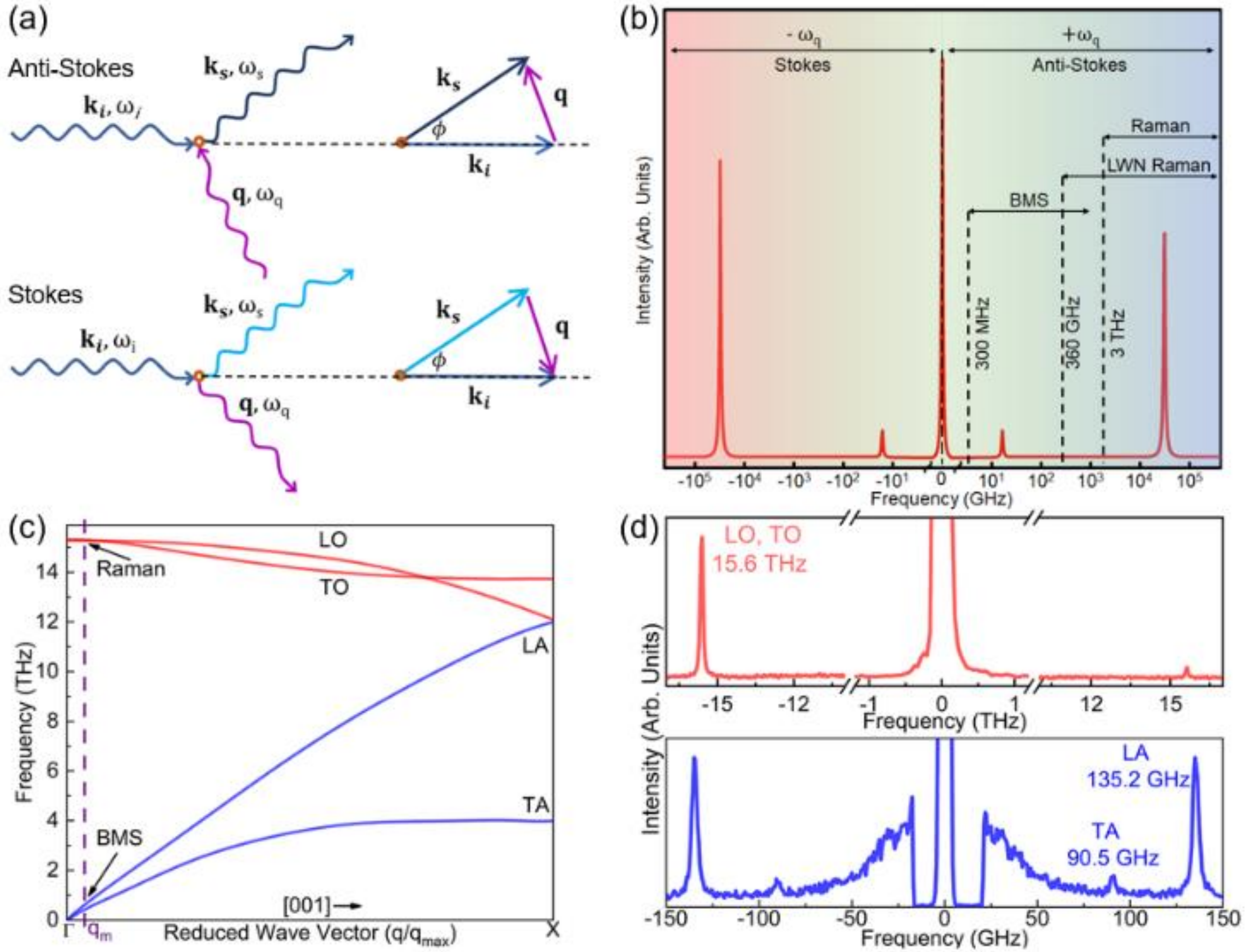


- Phononic crystals modify the phonon bands due to the artificial periodicity imposed on the material;
- Bandgap opening is possible with correct selection of geometry and material.

F. Kargar, A.A. Balandin, Nature Photonics. 15 (2021) 720–731;
Graczykowski et. al, Phys. Rev. B 91, 75414 (2015)

Introduction to Brillouin-Mandelstam Spectroscopy

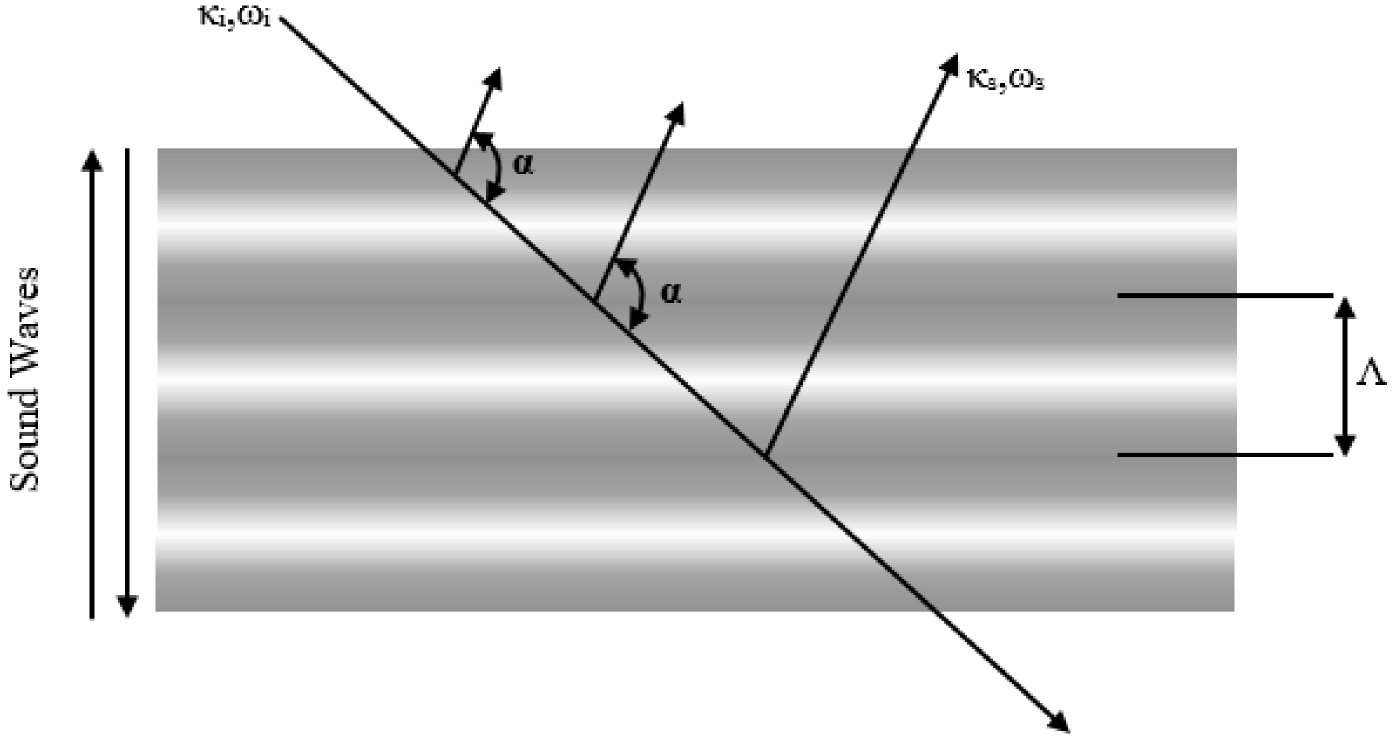




- ➢ Observing acoustic phonons in inelastic light scattering is more challenging than observing optical phonons.
- ➢ BMS system coupled with our low-wave number (LWN) Raman cover phonon frequencies from sub-GHz to hundred THz;

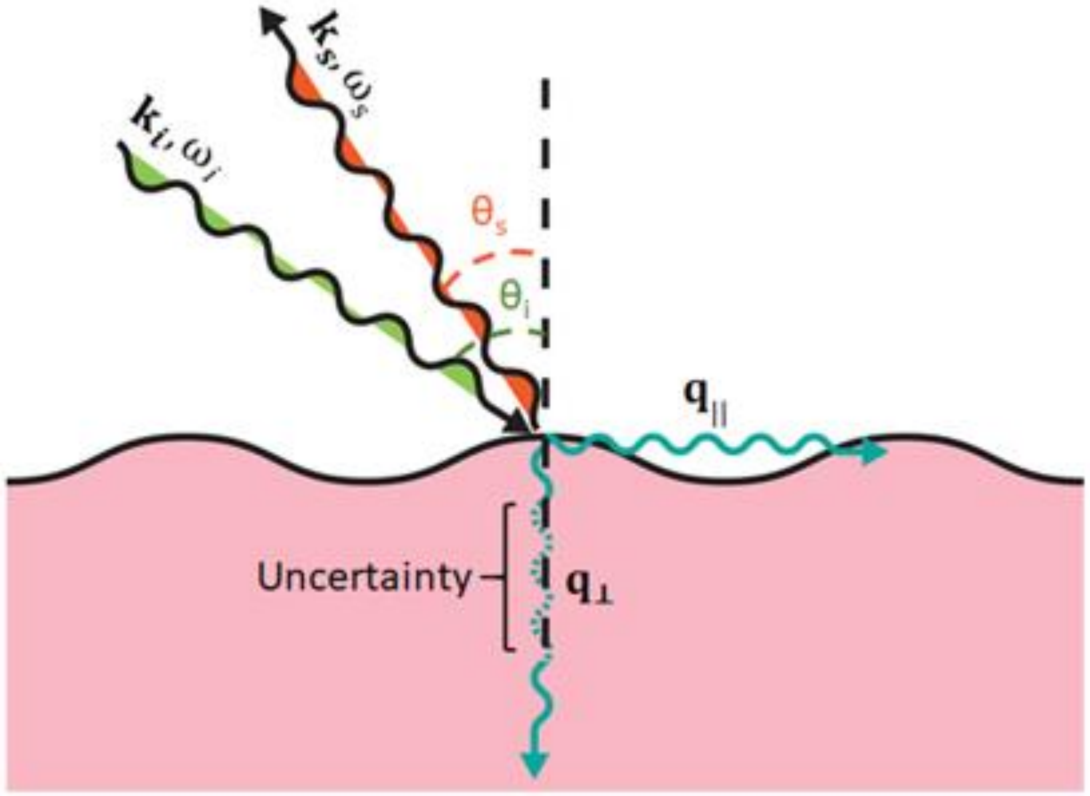
F. Kargar, A.A. Balandin, Advances in Brillouin–Mandelstam light-scattering spectroscopy, Nature Photonics. 15 (2021) 720–731. https://doi.org/10.1038/s41566-021-00836-5.

Scattering by Surface Ripple Mechanism



$$q_B = 4\pi n/\lambda$$

- Phonon wavevector depends on n and λ
- n: refractive index of the material
- λ: laser excitation wavelength



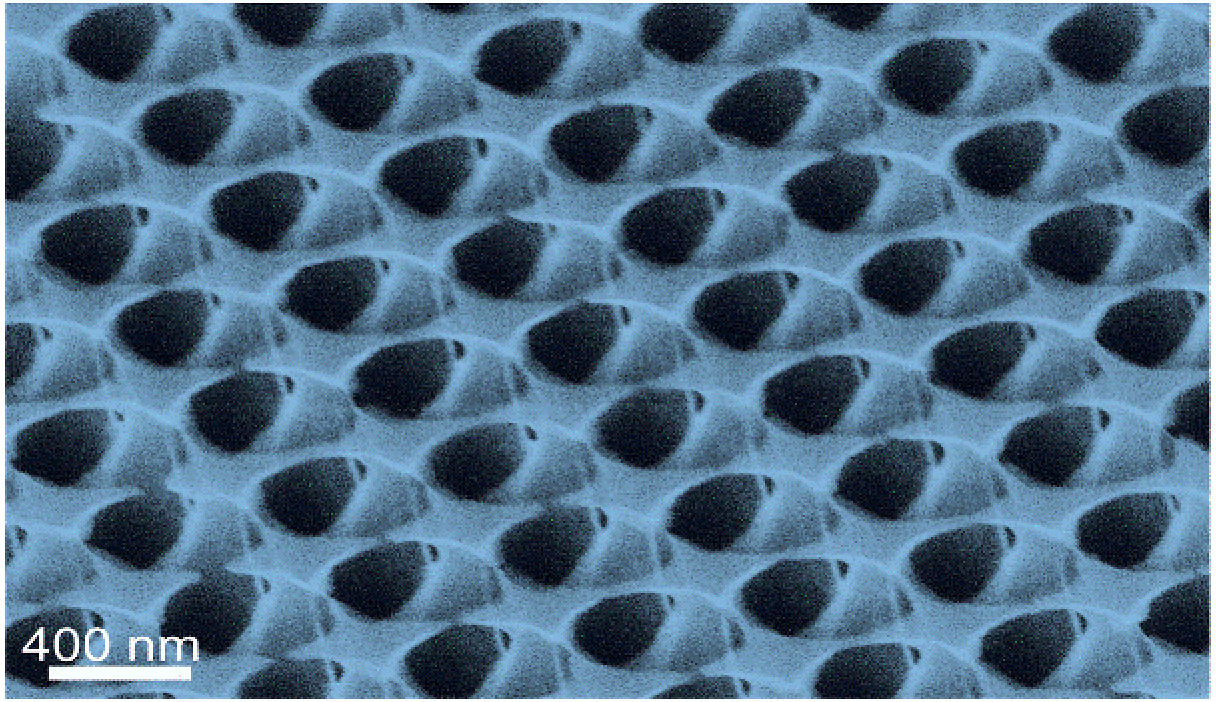
$$q_S = (2\pi/\lambda)\{\sin\theta_i - \sin\theta_s\}$$

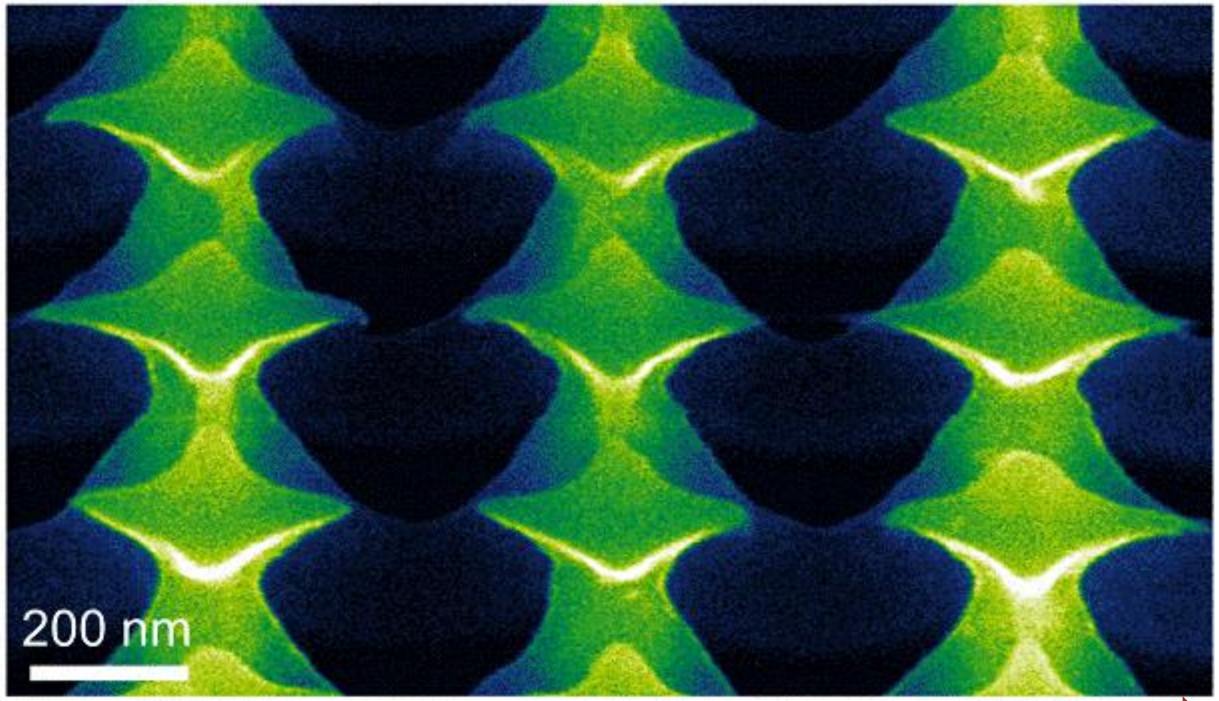
$$\theta_i = \theta_s = \theta \rightarrow q_S = (4\pi/\lambda)\sin\theta$$

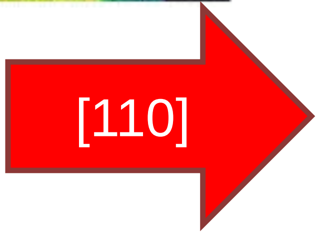
- Changing the incident angle changes the phonon wavevector → obtain phonon dispersion

F. Kargar, A.A. Balandin, Advances in Nat. Photonics. 15 (2021) 720–731.
Sandercock, J. R. in *Light Scattering in Solids III. Topics in Applied Physics* (eds. Cardona, M. & Güntherodt, G.) vol. 51 173–206 (Springer, 1982).

Pillars with Graduation Hat Structures



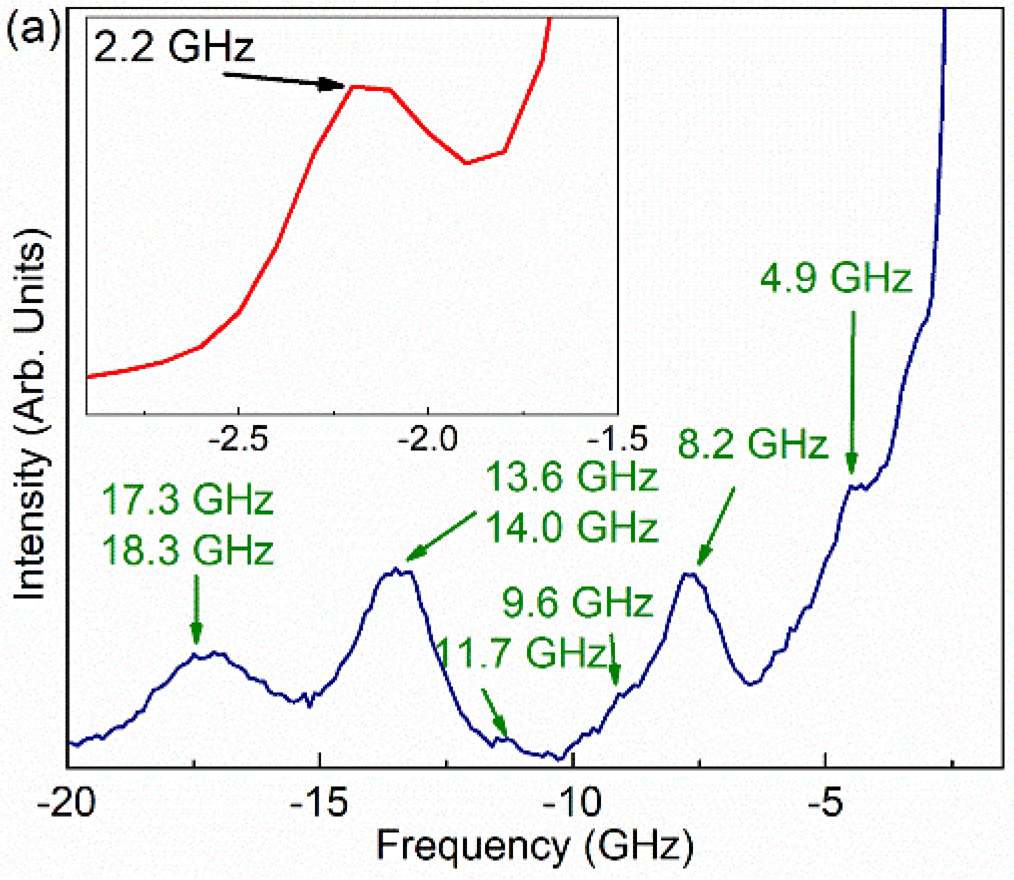




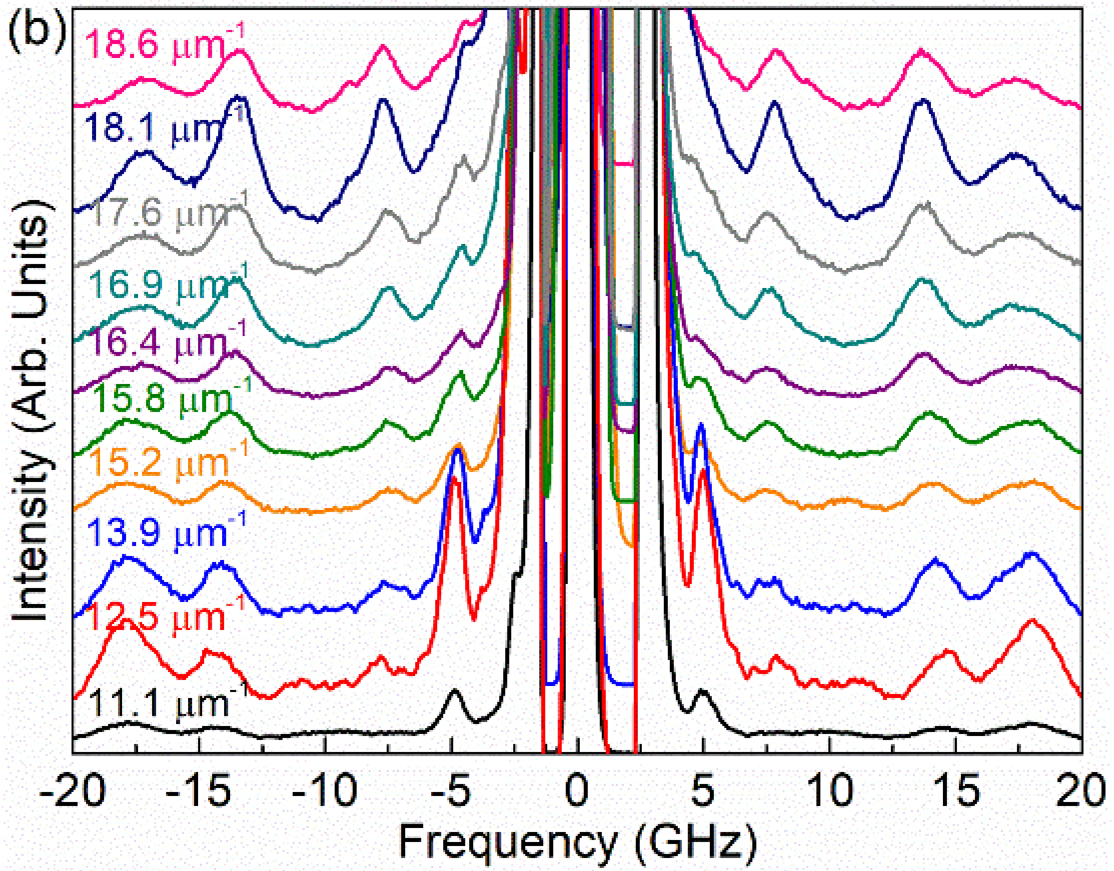
- Scanning electron microscopy (SEM) images of the ordered pillars with specific design.
- This pillar array behaves as phononic and photonic material.
- Periodicity: ***500 nm***; Height: ***362 nm; Hat lateral dimension: 362 nm***

Huang, C. Y. T. *et al.* Phononic and photonic properties of shape-engineered silicon nanoscale pillar arrays. *Nanotechnology* **31**, 30LT01 (2020).

BMS Spectra of Pillars with Hats



- ➢ Evolution of BMS peaks with increasing the phonon wave-vector;
- ➢ Samples are patterned and opaque: BMS spectrum dominated by surface ripple mechanism;
- ➢ Changing incident angle, so does the phonon wave-vector



- ❑ 9 distinct peaks attributed to the resonance and confined phonons.
- ❑ Very sharp peak at ~2 GHz.
- ❑ The intensity of this peak is not comparable with the rest.

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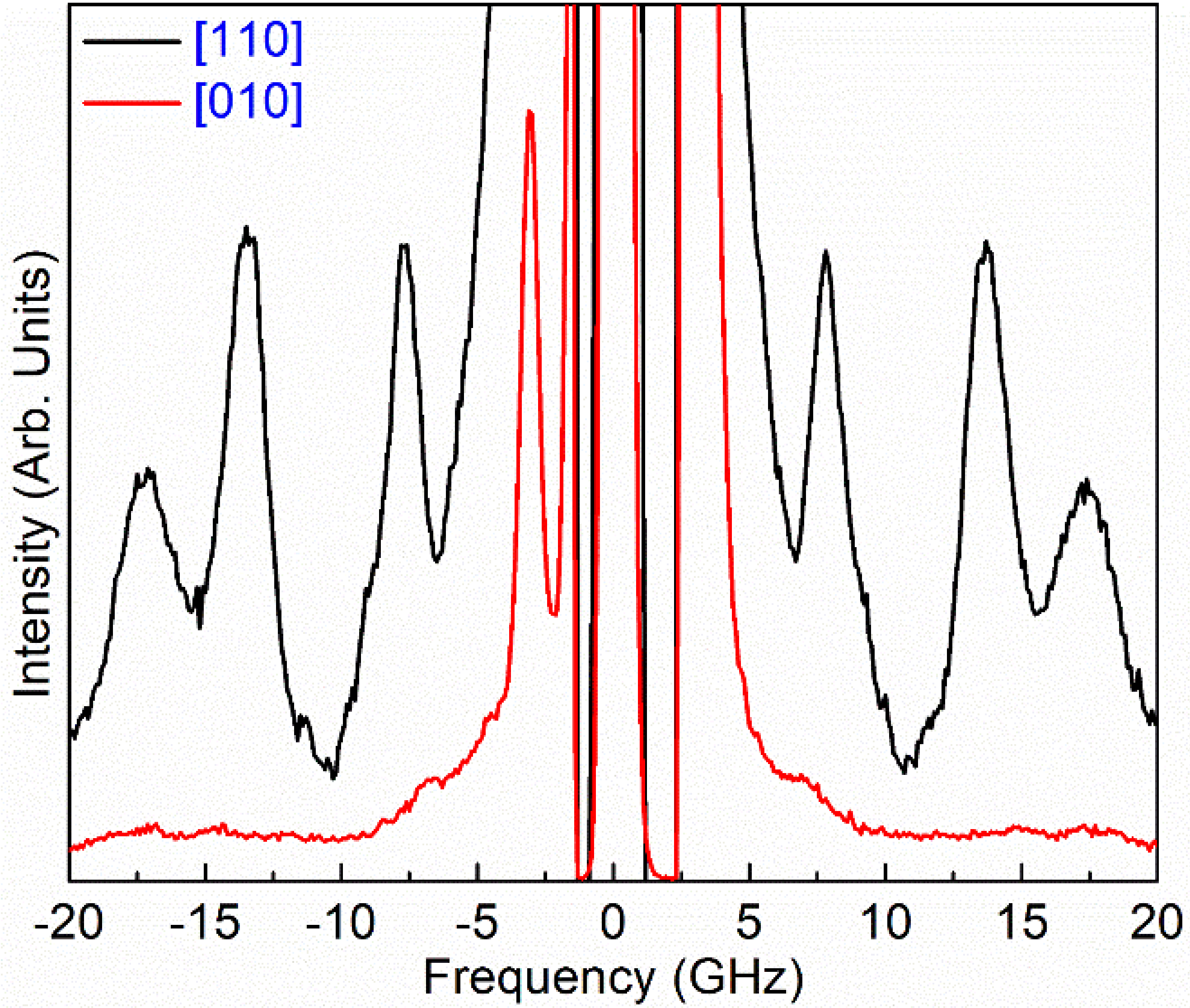
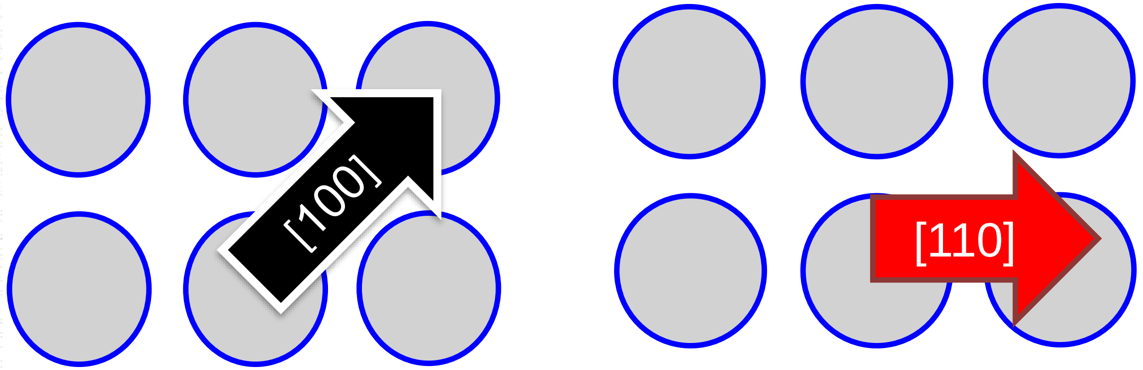
Confinement or Periodicity Effects?





- Different crystallographic direction, some modes survives while others disappears;
- The remaining modes are localized phonon modes for certain.
- Disappeared phonon modes: either as a result of rotation or weak interaction with light

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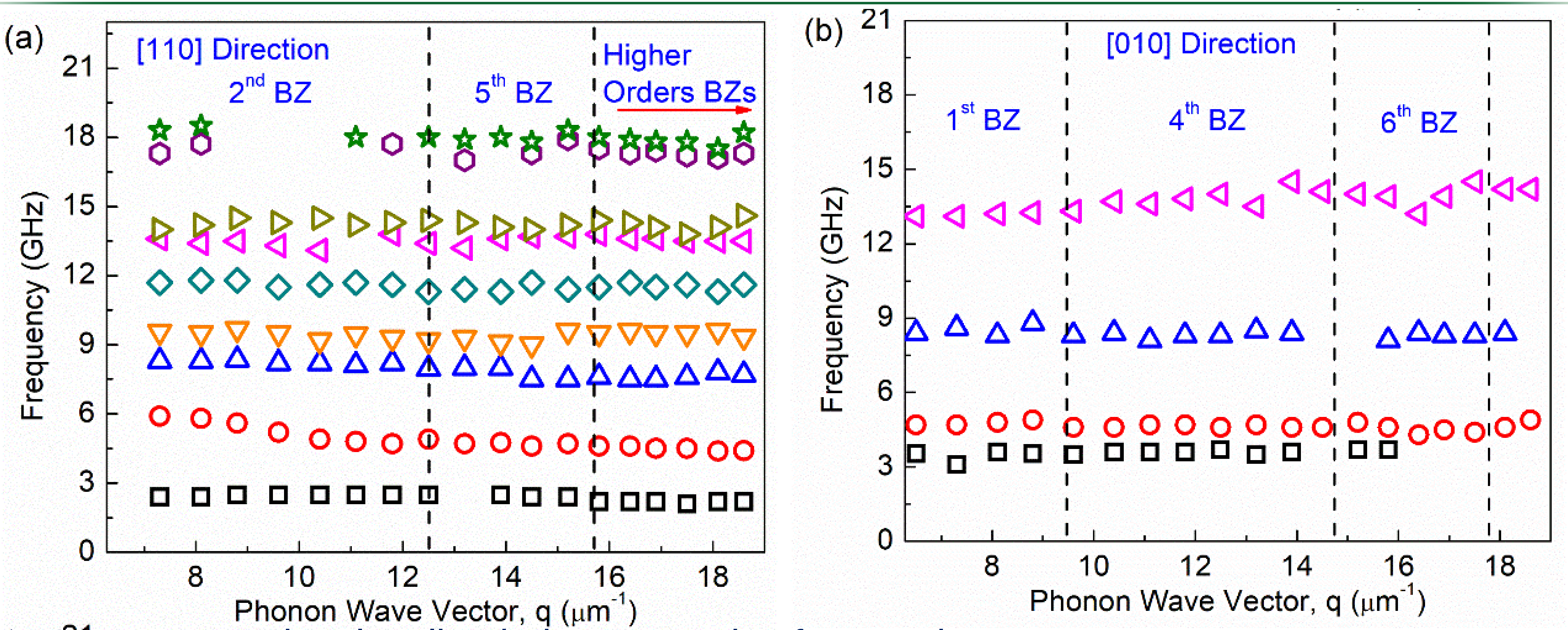
Flat Phonon Bands Along Both Directions



- ➢ Common modes: localized phonon modes for certain.
- ➢ Disappeared phonon modes: either as a result of rotation or weak interaction with light;

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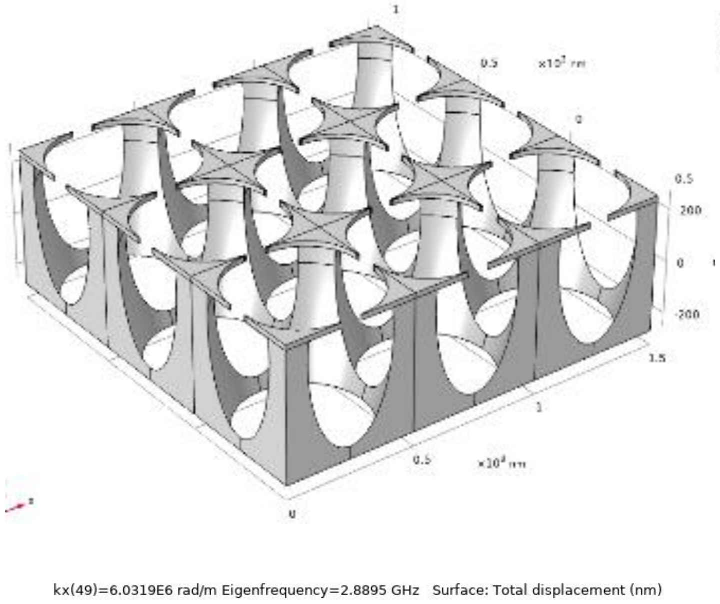
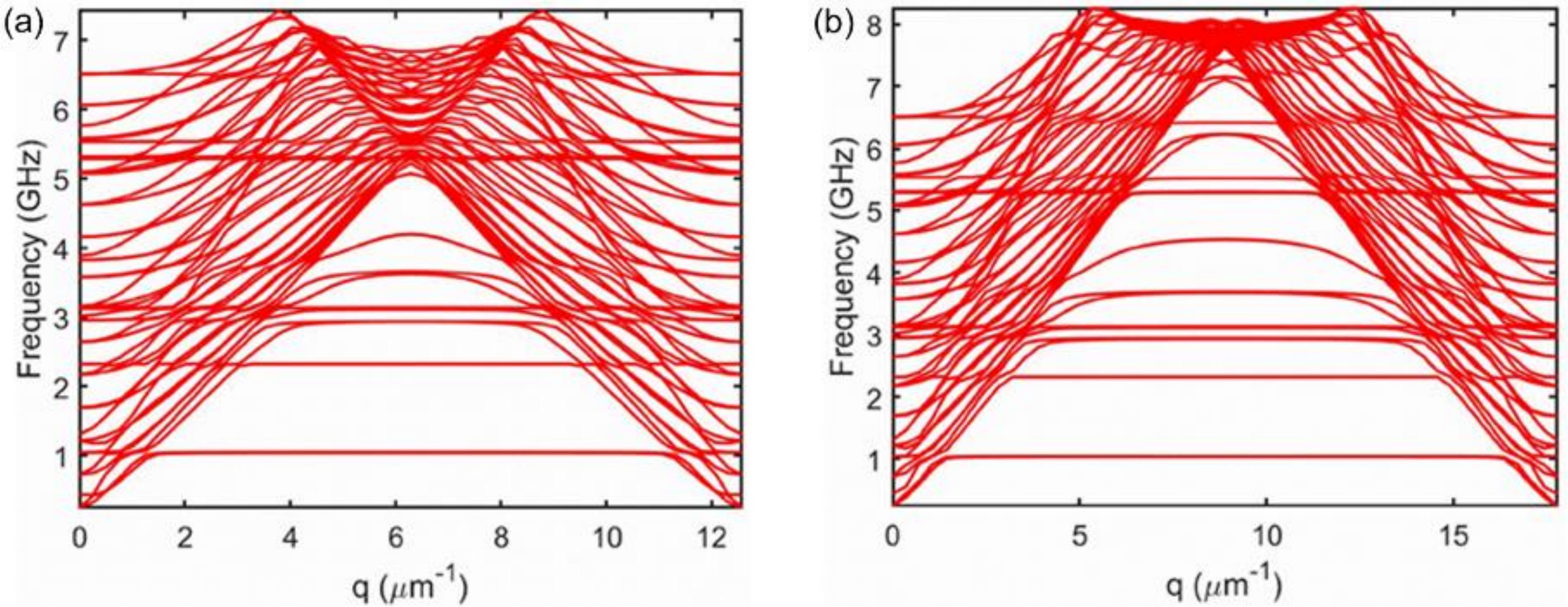
Theoretical Simulations





- COMSOL simulations have been conducted to obtain the phonon dispersion at different directions.
- Assuming fixed boundary condition, many flat bands appear and do not start from zero.
- In high frequencies more than 10 GHz, the dispersion becomes a spaghetti of phonons.

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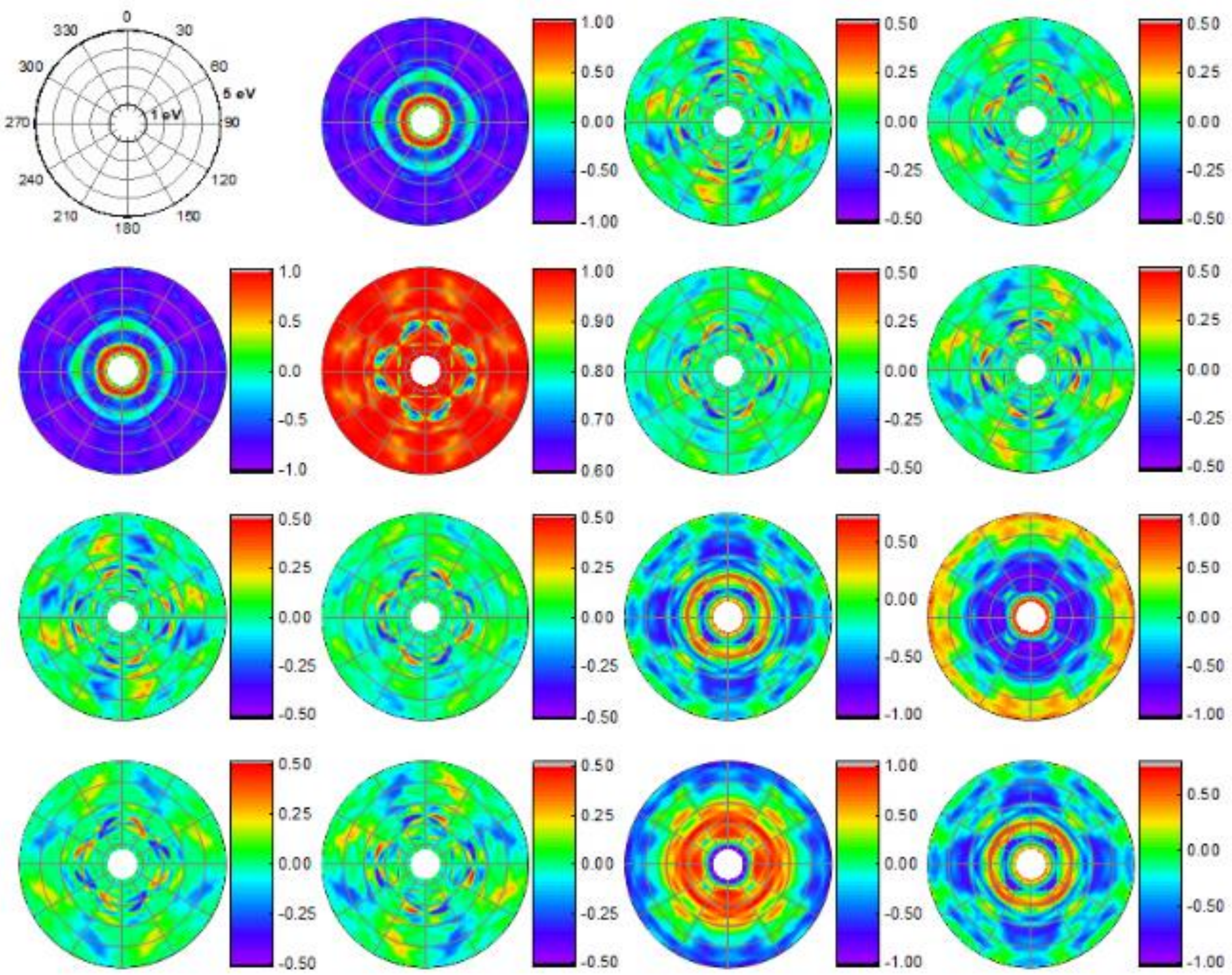
Four-Fold Symmetric Ellipsometry Data



- The Mueller matrix represents the most general description of light interaction with a sample or optical element, including depolarization and scattering effects;

$$\begin{pmatrix} S_0 \\ S_1 \\ S_2 \\ S_3 \end{pmatrix}_{out} = m_{11} \begin{pmatrix} 1 & m_{12} & m_{13} & m_{14} \\ m_{21} & m_{22} & m_{23} & m_{24} \\ m_{31} & m_{32} & m_{33} & m_{34} \\ m_{41} & m_{42} & m_{43} & m_{44} \end{pmatrix} \begin{pmatrix} S_0 \\ S_1 \\ S_2 \\ S_3 \end{pmatrix}_{in}$$

$$S_0 = I_p + I_s$$
$$S_1 = I_p - I_s$$
$$S_2 = I_{+45°} - I_{-45°}$$
$$S_3 = I_{\sigma+} + I_{\sigma-}$$

- Polar contour plots of the normalized Mueller matrix spectroscopic ellipsometry data obtained at an angle of incidence of 70°.
- Distinct scatter pattern of four-fold symmetry due to the symmetry and periodicity of the pillar array

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Summary and Conclusions

- Specific pillar phononic-photonic structures were fabricated with controllable hat structure;

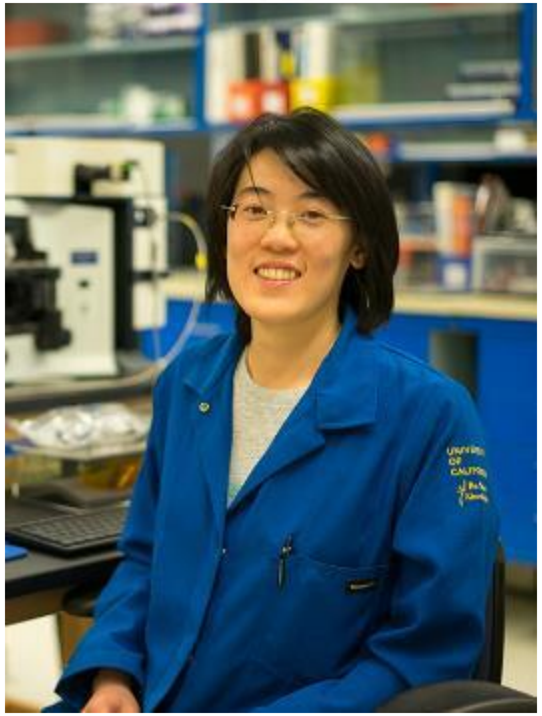
- With using BMS, we were able to distinguish localized phonon modes.

- The experimental and theoretical study of our nanostructure demonstrates both phononic and photonic behaviors.

- Localization of light as well as localization of phonon modes in the hat give rise to very intense peaks at BMS spectrum indicating an enhanced interaction of light with phonons.

- Theoretical simulations of phonon band structure confirm the experimental results.

Acknowledgments



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